LATE PLEISTOCENE GEOLOGY
OF THE KOWAI RIVER VALLEY
MID-CANTERBURY

with 5 separate maps

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ABSTRACT

The Kowai River Valley, a formerly glaciated tributary of the Waimakariri River, drains the eastern side of the Torlesse Range in the vicinity of Porter's Pass.

A study of the glacial deposits and stratigraphy was made, investigating three specific but complimentary aspects:

(1) Mapping of the glacial stratigraphic succession for the purpose of correlation with that established for the Waimakariri River System (Gage, 1958);

(2) a detailed comparative textural analysis of outwash gravels from two glacial advances to determine whether any significant differences exist, that can be directly related to environmental processes operating during transportation and deposition of these materials;

(3) a clay mineral study of weathering products as a potential tool for age determination and correlation.

From logitudinal terrace profiles, a distinct surface and moraine system was found for each of the Woodstock, Otarama, Blackwater I and II and Poulter Glacial Advances, from which their magnitude and maximum extension were interpreted.

The stratigraphy and glacial history of the Kowai River reflects that of the Waimakariri River very closely, but, several anomalous topographical features indicate that the Kowai Valley traverses a zone of active tectonism.

The principal sites of movement were identified and something of the tectonic history was deduced.

Parameters measured for the gravel analysis included size distribution, composition, sphericity and shape factor. Correlations between parameters were sought. Comparisons of parameters between samples were made. Variations in size distribution between samples were explained in terms of local hydraulic conditions during deposition, selective sorting and abrasion by ice and subsequent fluvial transportation. Variations in compositional types between samples resulted from (1) increase or decrease of other rock types, (2) relative abundance and availability in source area, (3) influx of new material and (4) local sample variation.

Similarity of sphericity values and dominance of disc-shaped particles for both samples reflects the importance of the mechanisms and processes during transportation within a glacial environment.

Clay samples from five stratigraphic sections of Late Pleistocene glaciofluvial deposits, representing all the major advances, were analysed using X-ray diffraction and infra-red spectroscopy techniques. Differentiation between units of gravel was attempted using the relative intensities and peak area measurements of (001) basal reflection.

The $7A^{o}:14A^{o}$ intensity ratio was used as an indicator of the degree of weathering with moderate success.

The clay mineral assemblage within distinct gravel units is not sufficiently characteristic to be used as a consistent and accurate means of correlation, unless the duration of a particular glacial episode is such as to enable the clays to develop specific characteristic attributes prior to burial.

In conclusion the main contributions of this study have been:

(1) the recognition of the extent and activity of the Porter's Pass Fault Zone and the importance of taking this into account when correlating glacial deposits across this zone elsewhere,

(2) The establishment of a detailed body of textural data on glacial outwash gravels for future comparative purposes,

and

(3) an indication that there is potential to further investigate weathering products as a correlative tool.

CONTENTS

SECTION ONE PHYSIOGRAPHY

CHAPTER PAGE

SECTION TWO SEDIMENTOLOGY

PART ONE

PAGE

SECTION TWO

PART TWO

CHAPTER PAGE

TABLES

PAGE

FIGURES

SECTION ONE - PHYSIOGRAPHY

CHAPTER ONE

BACKGROUND

I. INTRODUCTION

This work is presented in two sections. The first considers the physiographic expression and development of certain stream terraces within the Kowai River Catchment, a tributary of the Waimakariri River draining Canterbury foothills west of Springfield, with the view to constructing the sequence of glacial events that took place during the Late Pleistocene Epoch.

Mapping of the associated deposits was also undertaken. These included a variety of superficial glacial, fluvioglacial and periglacial deposits.

During the course of this investigation it became increasingly evident that this was going to be a more complex task than first anticipated. In particular, many anomalous topographical features such as tilted glacial terraces, disrupted drainage patterns and synchronous massive landslides defied a simple explanation.

Perseverance eventually led to the discovery of a massive fault zone extending across the area, that showed signs of being active during the Late Pleistocene. The principal sites of movement were identified and something of the timing of movement relative to the major glacial events within the Kowai System was deduced.

The second section consists of two parts, the first of which is concerned with the sampling and analysis of materials from the sequence of aggradational outwash terrace levels that line the Kowai River.

Because the field of sedimentology has advanced rapidly with the advent of modern methods of sediment analysis, the emphasis has shifted from the purely descriptive aspects of the science to an analytic approach. With this change in viewpoint the fundamental attributes of sedimentary particles have received much attention. These attributes such as size, shape and sphericity, to name but a few, have been extensively studied by mathematical and statistical methods.

The results of such methods has been to furnish a large amount of data which again tend to be merely descriptive. Far more important than the fact that a gravel deposit has a specific type of size frequency distribution is the statement of what genetic factors were involved in producing that distribution.

The statement of these genetic factors involves a study of environments of deposition and, in addition, knowledge of the previous history of the material being deposited. This knowledge has too often been derived from theoretical reasoning rather than experimental fact. The present research has been conducted with the purpose of (1) adding to this knowledge by means of field observation and (2) to explore the possibility by comparing the attributes of sedimentary particles, of finding possible discriminants for diagnostic properties of the age of particular glacial events.

The second part of section two is concerned with the possibility of differentiating units of outwash gravel of different ages, by discerning whether or not they differ in their clay mineral content as a reflection of differences in weathering history, and if so to test the limitations of clay mineralogy for correlation purposes. With the use of x-ray diffraction and Infra-red Spectroscopy techniques, clay samples from several stratigraphic sections of Late Pleistocene outwash gravels were analysed. The criteria considered, apart from clay mineral assemblage, included:

(1) the relative intensities and peak area measurements of (001) basal reflections of the constituent clays and

(2) the $7A^o:14A^o$ intensity ratio.

The latter ratio was used as an indicator of the degree of weathering.

II LOCATION

This thesis is concerned mainly with the north-eastern half of the Springfield sheet (S74) and the southern margin of the Broken River Sheet (S66), of the N.Z.M.S. topographical map series. (Figure 1.) The northern margin lies along the line of foothills to the north of the Little Kowai River. The eastern boundary coincides with the Waimakariri River and the southern boundary is an arbitary line running the length of the Russell and Big Ben Ranges. The Torlesse Range forms the western boundary. These boundaries define an area of approximately 50 square kilometres.

Several substantial mountain peaks exist within the area, the highest being Castle Hill Peak, 1998m. Others include Mount Torlesse 1963m, Foggy Peak 1734m and Ben More 1658m.

The main river, the Kowai, a tributary of the Waimakariri River, has numerous tributaries which include the Little Kowai, Rubicon, Brooksdale, Thirteen Mile Bush Stream, West Branch Kowai and Foggy River.

A series of terrace levels along the major drainage systems slope rapidly towards the east, being at an elevation of approximatly 1068m at the base of Mount Torlesse, and falling, in a distance of 24 kilometres, to about 366m at the eastern end of the

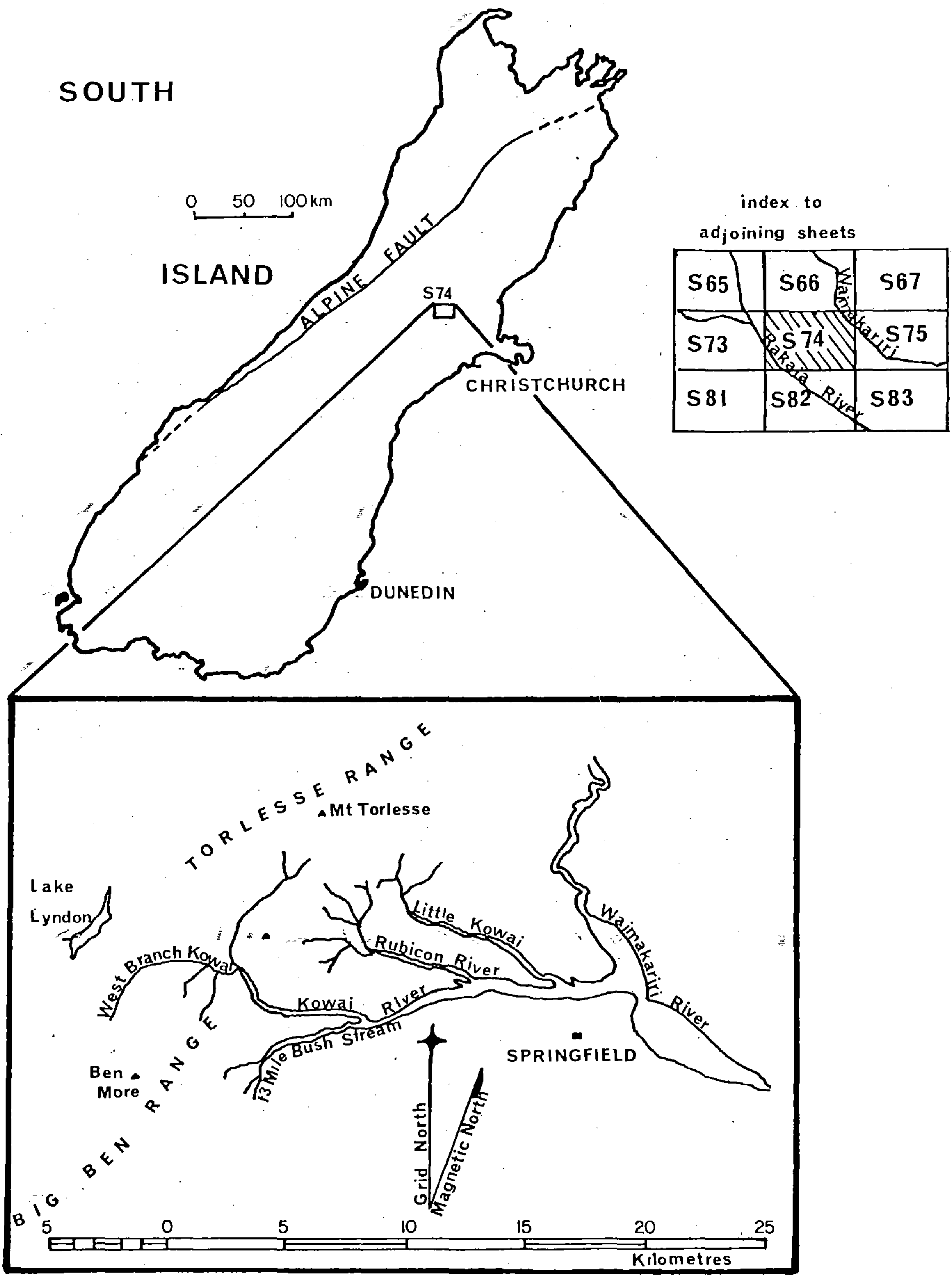

Fig 1.1 Location of study area.

Malvern Hills.

III ACCESS

Road access from Christchurch, 72 kilometres away is via the main West Coast Highway. This highway provides good access between the township of Springfield and Porter's Pass (930m). Secondary roads enable reasonable access, particularly along the lower reaches of the Kowai Catchment; however, access to the remainder of this catchment is poor and was accomplished on foot.

IV VEGETATION

A wide variation in altitude and climate together provide a wide range of plant habitats, hence a rich and varied flora. The two most important physiognomic vegetation types are beech forest and fescue tussock grassland. The remainder of the area is occupied by high altitude grassland, high altitude scrub, bog, scree and rock. Historic factors such as fires in pre-European and recent times, and sheep grazing for the last 100 years have also had extremely important effects in combining to produce variety in the flora.

The vegetation within the Kowai Catchment is broadly classified as:

(1) Grasslands

Native grasslands have been oversown with red and white clover. The principal native grasses include sweet vernal (*Anthoxanthum odoratum*), browntop (*Agnostis tenuis*), and blue wheat grass (*Agropyron scabum*). They are usually found in association with various short tussock species including Silver tussock (*Poa caespitosa*), blue tussock (*Poa colensoi*) and hard tussock (*Festuca novae-zelandiae*), the latter two species being dominant.

Mosses and sedges occupy the bogs and tarns.

(2) Shrublands

Shrubs of the lower altitudes include manuka (*Leptospermum scoparium*), matagouri (*Discaria toumatau*), native broom (*Carmichaelia spp.*), speargrass (*Aciphylla spp.*), and in localised areas gorse (*Ulex europaeus*).

In the sub alpine zones the main shrub species include the snow totara (*Podocarpus nioalis*), celery pine (*Phyllocladus alpinus*), species of vegetable sheep (*Raoulia*) and patches of *Dracophyllum*.

(3) Forests

For all practical purposes the forests of the Kowai catchment may be described as mountain beech (*Nothofagus solandri var cliffortioidus*) forests. All other tree species are of minor or negligible importance.

Black beech (*N. solandri var solandri*); is found only in remnant pockets of beech-podocarp forest on the plains near the confluence of the Kowai and Waimakariri rivers.

V PREVIOUS WORK OF THE AREA

This area was first explored by Von Haast in the 1870's. Hutton (1883) refers to the deposits and glacial landforms of the region in some detail with particular mention of the origin of Racecourse Hill, Little Racecourse Hill and several other mounds protruding above the level of the plains in the vicinity of the township of Springfield.

Speight (1924) wrote a comprehensive geological account on an infaulted outlier of Tertiary marine sediments within the West Branch Kowai Catchment. He refers to various glacial deposits within the Kowai Valley. A discussion on the possible limits of glacier ice from the Waimakariri and Rakaia Rivers incorporates a summary of the views held by Von Haast and Hutton.

Speight saw no convincing evidence for significant interglacial episodes. Gage (1958) outlines evidence for an interglacial stage and several interglacial substages. The sequence of ice advances and withdrawals indicated by the deposits in the Waimakariri River Valley formed part of the basis of a proposed scheme for New Zealand glacial stages introduced by Gage and Suggate in 1957. This scheme has been adopted for use in this study.

Gage and Moar (1972) re-examined the Joyces Stream evidence which they conclude adds support to the full interglacial status of the Woodstock/Otarama interval. (Gage 1958; 1961.) The glacial deposits of the Lower Kowai Valley were mapped on Sheet 18 Hurunui "Geological Map of New Zealand 1:250,000" by Gregg in 1964.

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CHAPTER TWO

GENERAL GEOLOGY

I LITHOLOGY

(1) Basement Rocks

The basement rocks of the Kowai Valley Catchment consist of a great thickness of sandstones, siltstones, mudstones and cherts belonging to the 'Torlesse Facies' (Fleming, 1970), of Upper Paleozoic-Mesozoic age.

Superficially, the rocks are lithologically uniform, mostly grey, highly jointed, highly indurated massive sandstones and argillites of low metamorphic rank (prehnite-pumpellyite facies of Coombs et.al, 1959).

The matrix is very fine grained and makes up a considerable percentage of the rock composition. Lithic rock fragments and clastic mineral grains are embedded in the matrix. Some are feldspathic litharenites (Folk, Andrews and Lewis, 1970), in which rock fragments predominate over quartz and feldspar; the remainder are lithic feldsarenites.

The average argillite is a black to grey, poorly sorted, thinly laminated, fissile and well indurated muddy siltstone, dark to light grey in colour when fresh and slightly lighter when weathered. The clayey matrix consists of sericite and slightly recrystallized chlorite. Argillites are found in the field as interbeds between massive sandstone units.

These interbeds are of variable thickness and vary widely in geometry. Multiples of interbedded sandstones and argillites abound throughout the headwater regions of this area.

Quartz, orthoclase, plagioclase, chlorite, epidote and biotite are the principal clastic grains found in the sandstones and argillites. (Blair, 1972.)

Red and green, fine grained cherts, characterised by the presence of radiolarian casts, are intensively sheared and weathered. Many microcrystalline quartz particles and veins, but by no means all, have been replaced by clear calcite, epidote and chlorite.

Conglomerates and breccias consisting of mudstone clasts of pebble, granule and sandy-granule size together with sandstone particles have been found in streambed material but as yet have not been observed in outcrop.

Most thick and very thick beds of sandstone are outwardly structureless, and close examination shows this to be true over large parts of each bed, especially thick beds. However, abraded outcrops also reveal that zones characterised by primary sedimentary structures are scattered through such beds. (Andrews, 1972.) Examples of ripple cross-stratification and parallel laminations abound throughout the area but tend to be concentrated in zones of fine sandstone and very fine sandstone. Cross lamination is commonly load deformed, at places changing upward to totally contorted convolute-like lamination. Flame-like contortions apparently unrelated to cross-lamination occur in some horizons. Small-scale penecontemporaneous faults and small soft sediment expulsion structures also occur.

The black argillite is massive in outcrop but slab specimens show it to consist largely of discontinuous faint parallel laminae.

No fossils are known with the exception of rare vertical burrows and isolated specimens of '*Torlessia mackayi*', an Upper Triassic annelid.

Throughout the catchment these basement rocks are intensively faulted and folded. Fault crush zones abound throughout the area. Almost without exception the attitude of the bedding lies at very steep angles and in many cases is vertical.

(2) The Cretaceous and Tertiary Sequence

The Benmore Outlier of the Malvern Cretaceous series is located within the West Branch Kowai Valley approximately five kilometres from its junction with the Kowai River, lying immediately south of Porter's Pass in that gap which divides the Big Ben and Mount Torlesse Ranges.

This outlier is approximately two kilometres in length and with a varying width of up to one kilometre at its widest part. The height above sea level varies from approximately 610 to just over 915 metres.

At the base of the sequence coal measures rest unconformably on the greywacke.

> "The contact beds are much disturbed, slickensided, crushed and apparently overturned along a fault, as if the greywacke had been thrust against them from the south-east. The fault strikes NE-SW. It is impossible to determine the amount of throw from the exposures."
> (Speight, 1924.)

A rhyolite conglomerate occurs at the base of the sequence resting on a stripped greywacke surface. The conglomerate is similar to one which occurs at the base of the Cretaceous series elsewhere in the Malvern Hills, notably the Rakaia Gorge, White Cliffs and on the south-eastern slope of Mount Misery. A similar conglomerate occurs in the basin of the Kowai at the bridge across the Kowai River, where there is a small exposure of coal-measures, this being the nearest recorded occurrence of a bed similar to that occurring at Benmore.

The remainder of the West Branch Kowai sequence consists of shales and sands with coal, oyster beds with intercalated clay and interstratified sands and shales. The sands are of varying colour - grey, brown with oxidised iron, green with glauconite, and yellowish-white passing into white - all dipping south-east at an angle of 30°. (Speight, 1924.) These sediments are intruded by massive basalt sills and dykes.

The dykes are formed of very basic basalt. In a groundmass composed of feldspar laths, augite granules, and rather long individuals of magnetite with skeletal outline of ilmenite, there are many phenocrysts of olivine and augite, the former predominating in number. Some of these show signs of serpentinization, but they are usually fresh and colourless. Others have rims stained with oxide of iron. They, as well as the augite, frequently form aggregates. (Speight, 1924.)

The only other known occurrence of basalt dykes is within the upper reaches of Irishman Creek, where they seem to be vertically inclined. Nearby is an intrusive body of dolerite.

Another outcrop of dolerite can be found behind the township of Springfield. (Trig E, 435 m) Map I. Neither the extent or the geometry of either of these dolerite bodies is known.

II GEOMORPHOLOGY OF THE KOWAI AND TRIBUTARY VALLEYS

From the base of Mount Torlesse the Kowai River descends 700 metres over a distance of approximately 24 kilometres, eastwards towards the Waimakariri River of which it is a tributary.

The Kowai River itself has several major tributaries. The Little Kowai, Rubicon, Brooksdale and Kowai Rivers drain the foothill area lying to the north of the Kowai River, while the Foggy and West Branch Kowai Rivers, together with Thirteen Mile Bush Stream, drain the western and south western foothills including the Torlesse, Big Ben and Russell Ranges.

The area through which these rivers flow was extensively glaciated during the Late Pleistocene. Although at present no permanent ice remains, the valleys and foothills display abundant evidence of glacial activity.

A striking feature of the rivers is the absence of waterfalls and cascades along their entire courses which suggests that river channels were deepened below their present level during a former time, undoubtedly by a combination of glacial and fluvial processes. (Profiles I, II, III.)

(1) <u>Kowai River</u>

In the upper reaches the river valley is often no wider than 50 metres, the sides of which rise steeply and are composed of exposed, highly fractured, sandstone bedrock. The river course at its widest part is a mere ten metres across, where it has cut into drift. Where the river course is incised within bedrock it becomes exceedingly narrow.

From its source to the bedrock gorge section immediately above its junction with Torlesse Stream, the Kowai river bed consists of a series of pools and riffles due mainly to the coarse nature of the bedload,

Bedload consists essentially of very large boulders, many of which exceed several metres in diameter and behind which smaller sized material has accumulated. The stream gradient along this section of the river is particularly steep but lessens markedly below the gorge. Thereafter the Kowai River spreads out over a very wide area, particularly where it has cut into glacial deposits. The bedload here is considerably finer and the first signs of braiding are apparent. Further changes in gradient are frequent and are associated with sections of the river where additional bedload is brought into the Kowai River by tributaries such as Foggy River, or where it crosses the major crush zone.

The Kowai River does not have the competence to remove the excessive bedload brought down by the Foggy River under normal flow conditions so that material tends to accumulate at this confluence until flushed out during periods of peak flow. The rate of influx of material is greater than can be removed. This stockpiling has in effect produced a barrier across the Kowai River and accounts for the very steep gradient across the Foggy river mouth confluence. (Profile II.)

Below this confluence the Kowai River is aggrading rather than degrading. Several gorge sections of bedrock through which the Kowai River has cut, act as bottlenecks through which very little bedload passes. Instead this material accumulates on the upstream side of these gorge sections, within widened segments of river bed that have been partially cut into glacial drift and partially into bedrock.

Below the last gorge section, immediately downstream from the junction between the Kowai and West Branch Kowai Rivers, the Kowai River bed opens out considerably. As it is no longer restricted by bedrock, lateral erosion into glacial outwash material is prominent. From this gorge to the mouth of the Kowai River the gradient is steep but falls at a constant rate. The width of the Kowai River mouth is approximately 400 metres and the depth of incision below the highest aggradational terrace level is approximately 98 metres. (ProfileI.)

(2) <u>Little Kowai River</u>

The headwater region of the Little Kowai River differs from that of the main Kowai River on several counts. These include:

(a) The headwater valley of the Little Kowai River is wider and more heavily vegetated by beech forest and tussock.

(b) The gradient of this river is much less steep and the bedload considerably finer.

(c) It drains a smaller catchment within foothill topography, comprising stripped bedrock surfaces.

(d) The rate of flow and the rate of bedload discharge are correspondingly small.

(e) This foothill catchment has not been glaciated since the Avoca Glacial Advance so that there are no aggradational or degradational terrace systems present.

The lower reaches, below the Caesar's Hill Surface, (Discussed more fully in Chapter Three) open out into a wide plain of aggradational outwash deposits into which the Little Kowai has cut a series of discontinuous terrace levels along its course. The river bed gradually widens and braiding becomes more pronounced towards its junction with the Kowai River.

(3) Rubicon River

The headwater region of this river is considerably wider and more open than the Kowai or Little Kowai Rivers. It is unique within this area in that the valley floor is completely filled with a thick deposit of river gravel, into which the Rubicon has cut. (Fig. 2.1.) A single terrace surface dips steeply, but at a constant rate, from the base of Papanui Road Range, against which it abuts, downstream to the junction of the Rubicon River and Beech Tree Stream. There it dives beneath a more recently constructed, gently sloping, terrace surface that extends from the Beech Tree Stream Catchment, down the Rubicon River to merge with the Kowai surface.

Fig. 2.1 View of Rubicon River looking towards 'Papanui Road Range'. Mount Torlesse is in top right corner. The photograph shows the extent of the gravel fill within this valley and the depth of incision of the Rubicon River. The position of Lake Rubicon is indicated by the arrow.

This period of aggradation not only filled the main Rubicon Valley but appears to have been rapid enough to backfill side valleys whose drainage once flowed into the Rubicon Valley. One such side stream, which is still blocked off, ponded up behind this barrier of alluvial gravel to form Lake Rubicon (Fig. 2.2). Swamp stream was temporarily backfilled to form a lake, evidence for which exists in the form of a lake silt deposit.

The Rubicon River is deeply incised into these fluvial deposits, of which the maximum particle size is approximately 30 cm in diameter. There is a hint that two periods of aggradation took place, for in the correct lighting the lower unit appears to be slightly darker in colour than the upper greyer coloured unit. (Fig. 2.3.)

A coarse deposit of rounded material resembling glacial outwash can be found in the interfluve area between the two branches of the Rubicon River draining Papanui Road Range. The source of this material and the volume of fluvial gravel flooring the Rubicon Valley is uncertain. Only in this interfluve area is there evidence, from a series of terraces cut into drift, that degradation took place as a series of distinct events. Along the remainder of the Rubicon River course within this upper catchment area, no degradational terrace surfaces have been preserved. The river bed is wide and braided except for two

Fig. 2.2 View of Lake Rubicon looking towards the Rubicon River which runs from left to right. The barrier behind the lake is composed of alluvial gravel that floors the complete valley.

Fig. 2.3 Close up of the Rubicon gravel units. The dark-brown coloured lower unit is overlain by a thinner deposit of greyish coloured material. The contact between the two units is indicated by the arrow. Both deposits contain numerous sand and silt lenses.

narrow gorge sections cut through bedrock. The fluvial gravel within the riverbed is so porous that frequently sections of the river bed run dry.

Along the lower reaches of the Rubicon River the valley opens out considerably. The river course cuts through glacial and post glacial deposits. These deposits include till, outwash, gravel, glacial silts and post glacial peat.

Flights of degradational terraces can be found along both banks of this section of the river.

(4) Brooksdale Stream

This stream arises from a series of low altitude foothills. It drains along a former lateral glacial drainage channel before emerging on to the Kowai Surface to meander along its northern margin. During a period of aggradation, outwash gravels from the Kowai River blocked off the Brooksdale Stream drainage, in the vicinity of the toe of the Benmore surface. Pondage behind the still visible barrier has created an area of swamp through which the Brooksdale Stream drains. Below the Brooksdale Homestead a marked change in the nature of this Stream can be seen. Headward erosion in an effort to establish an equilibrium with the Kowai River has resulted in deep gullying at the bottom of which this stream has developed a noticeable meander pattern. Good exposures of outwash gravel, deposits of grey coloured silt and clay deposits containing a substantial proportion of free size vegetative matter are to be found along this section of the Brooksdale Stream.

(5) West Branch Kowai and Thirteen Mile Bush Streams

The headwater region of Thirteen Mile Bush Stream is heavily vegetated with beech forest. No evidence to suggest that this valley has been glaciated has yet been found. This valley is floored with post glacial gravels into which the stream is shallowly entrenched.

The West Branch Kowai River catchment has been glaciated, but the extent of glaciation is uncertain. Within the wide, tussocked, upper catchment, isolated morainic remnants have been found. This river drains through an infaulted outlier of Tertiary deposits that include greensands, quartz sands and basalt dykes. The river bed itself is narrow as it is prevented from eroding laterally by numerous bedrock outcrops along its course.

Several high level surfaces of unknown origin exist along the mid-reaches. The only other feature worthy of mention is a series of degradational terraces cut into outwash gravel. These are of limited extent, width and vertical separation.

Along the lower reaches, near the Kowai River junction, the stream has cut a short way below a single terrace surface of post-glacial age.

CHAPTER THREE

LATE PLEISTOCENE GEOLOGY

I THE PROBLEM OF LOCAL STRATIGRAPHY

The basis of subdivision in a sequence of valley glaciations, rests on the well established methods of separating the associated deposits on altitude, distribution, morphology, depth of weathering and lithology.

The age of an episode of valley glaciation can be estimated by the amount of modification of glacial features affected by post glacial weathering and stream erosion or by estimating the duration of events that transpired since the waning of the ice. Thus one might note the accumulation of talus at the foot of the glaciated slopes, the modification of cirque form, or the weathering of till and outwash boulders. Similarly, the destruction of glacial lakes by filling or draining, the incision of streams into glaciated floors of till or bedrock, the erosion of moraines or outwash and the development of a soil profile on glacial debris are also important. Unfortunately, however, not all these criteria are present or useable in any one area. Because most of the criteria are qualitative, difficulties arise from the subjective nature of interpretation, which are common to most studies of this kind. In addition there are problems peculiar to this locality, stemming from the influence of active faulting on the drainage system.

One of the main difficulties lies in the small altitude differences between features of one glaciation and the next, in contrast to valleys such as those of the Rakaia and Waimakariri Rivers.

II NOMENCLATURE

Problems were encountered in trying to set up a sequence of time-stratigraphic units. based on climatic change, for the glacial stratigraphy of the Kowai Valley.

As one of the aims was to correlate and check the validity of the glacial stratigraphy established by Gage in 1958, for the Waimakariri River System it was decided to use the nomenclature already available.

As far as terrace levels are concerned, the complexity of the terrace systems in this area necessitated the naming of the major surfaces. This terrace nomenclature is advantageous in that reference to the various individual surfaces is greatly facilitated.

The series of names, derived from local topographic features and homesteads, is for local use only. When arranged in stratigraphic order the terrace stratigraphy can be used in conjunction with the time-stratigraphic succession of glacial advances. (Fig. 3.1.)

Although the nature and morphology of these surfaces is described before a formal stipulation of the history of glacial events is discussed, the time-stratigraphic nomenclature and interpretation has been given where relevant for simplicity.

III AIM

The three main objectives of this study were:

(a) To map the glacial and post glacial stratigraphy.

(b) To trace outwash gravel terrace levels from the Waimakariri River headward along the Kowai River and its tributaries to their respective moraines, and

(c) to correlate with and check the validity of the stratigraphy established by Gage in 1958, for the Waimakariri River System.

IV TERRACES AND OTHER SURFACES

The course of the Kowai River and its many tributaries is shown on the New Zealand Topographical Map of the N.Z.M.S. 1, One Inch to One Mile Series, Sheets S66 and S74.

The terraces of the Kowai River and its tributaries range in size from short remnants a few metres across to plains such as the Kowai Surface, Kowai Pastures surface and Mount Torlesse Surface,

MID CANTERBURY REGION		
Canterbury Glacial Advances		Correlated Surfaces
Rakaia Valley	Waimakariri and Kowai Valleys	
Post Glacial	Post Glacial	Channel deposits across Kowai Pastures Surface. Degradational surfaces along major river courses incised below the topmost aggradational surface.
Acheron Advance	Poulter Advance	
Bayfield II Advance	Blackwater II Advance	Kowai Surface
Bayfield I Advance	Blackwater I Advance	Part of Kowai Pastures Surface
Tui Creek Advance	Otarama Advance	Mount Torlesse Surface. Part of Kowai Pastures Surface.
Woodlands Advance	Woodstock Advance	Ayrdale Surface Annavale Surface Benmore Surface Caesar's Hill Surface
	Avoca Glaciation	

Fig. 3.1 Glacial Sequence in the Mid-Canterbury Region.

measured in kilometres.

Most terrace surfaces consist of coarse or bouldery gravel, though accumulated soil and intensive farming practices have masked much of the surface detail.

Exposed river sections can afford excellent criteria for correlation of terrace surfaces, as differences in the degree of weathering of most of the coarse bouldery gravels were sufficiently marked to distinguish one deposit from another in most instances. The thickness of the loess covering was also useful in identifying and correlating terrace remnants.

In places terrace levels occur in flights, with their outer margin cut into curved meander scars rising above old channels in the terrace below. The highest terraces are oldest, the lowest youngest. Had the terrace levels represented by present remnants been few in number and widely spaced vertically, it would have been easy to trace them along and across river. However, terraces are discontinuous, and levels are not sufficiently consistent to permit tracing them along valleys for great distances.

The most impressive sets of terrace levels are to be found below the Kowai and West Branch Kowai Rivers junction where the deposits are essentially aggradational, whereas above this junction many terraces consist of a rock bench with planed or channelled water worn surfaces overlain by various thicknesses of river gravel, local angular rock debris and soils, the surface of which constitutes the terrace level.

Complications in matching terrace surfaces arose due to the apparent height of many terraces being raised by the superimposition of alluvial fans built from side valleys. Three examples of this can be found within the vicinity of the 'Gut'. There are few exposures that permit the thickness of these fan deposits to be determined. However, the break in slope caused by the truncation of these fan surfaces by the Kowai River is interpreted here as representing a former level of aggradation. Great difficulty was encountered near bends in the streams in deciding to what position on the profile distant points should be projected.

(1) Fieldwork

It was essential to map the position and elevation of all terrace remnants. The field work was greatly facilitated by use of aerial photographs. Photographs from runs 2760, 2761, 2762 and 2763 were examined stereoscopically. All visible terraces were outlined and then verified by reconnaissance.

Elevations were determined using a Paulin Altimeter keyed to trig points and spot heights shown on the topographical maps of the area. Unfortunately many of these proved to be too distant and inaccessible for reliable and repeated use. Additional stations were set up at points along the course of the Kowai River that afforded easy access. These were established using a geodimeter in conjunction with a theodolite and are accurate to within a few centimetres. It is hoped that most of the elevations thus determined with the altimeter between the Waimakariri River and the Tussock Grasslands Field Station, including the Torlesse Stream Catchment are correct to within one metre.

Aneroid observations in the upper catchment above the field station are subject to error from abrupt local variations of barometric pressure, aggravated by the length of travelling time between the few available height control points. The error was reduced as far as possible by re-occupying all the stations on different days.

However, within this area the vertical separation of the terrace surfaces is of sufficient magnitude, and the horizontal distance such, that an attempt was made to determine heights solely with the aid of the altimeter. Although less exact, this data did distinguish the various terrace levels, many of which were traceable to their respective moraines.

(2) Moraines

In general it has been found that the moraines of each of the several stages are less extensive than those of the preceeding stages. Hence, in a particular valley the moraines nearest the head are the youngest and those farthest out are commonly the oldest.

Also worthy of note is the fact that moraines of the latest stage consist of hugh embankments of till while those of the earliest advances are either poorly preserved or completely non-existent.

In most cases a series of outwash terrace surfaces are traceable headwards to their respective moraines.

In topography there is much irregularity and usually little appearance of system. In general the moraines consist of a series of hummocks and short, irregular ridges, some of which rise fully 100 metres or more above the valley bottom. (Profile III). Stream erosion has in places deeply dissected the unconsolidated moraine deposits adding greatly to the topographic irregularity.

On the sides of many of the valleys within the Upper Kowai Catchment there are steeply descending ridges, sometimes composed of till, sometimes of stratified drift and sometimes of a mixture. They vary in height, breadth and details of form. While in some cases they have the appearance of erosional forms, as if carved out of drift by streams descending the hill slopes diagonally along the margin of the ice tongue as is seen immediately below John's Stream, they are more commonly, evidently of constructional origin. These forms are interpreted as marginal moraines built along the side and end of minor tongues which extended from the main valley tongues into the lateral valleys.

In the lateral valleys it is almost universally the case that moraines are much better developed on one side of the valley than on the other. In one case, in Moraine Stream, a remarkably perfect series of moraine ridges and moraine terraces are present on the north side of the valley, while a kame terrace of the same ice stand on the south side is weakly developed and of no great width. (Profile III.)

Sometimes stands of ice are not represented by ridges, but by a series of diagonally descending terrace levels radiating, fan shaped, from a former lateral-terminal moraine. At the Foggy River - Kowai River confluence it is evident that the separate strands represent halts in receding ice. The distance between the surfaces represents the distance through which the ice-front retreated horizontally during a vertical drop of a certain related number of metres on the main valley side. (Fig. 3.2.)

(3) Marginal and Outflow Channels

Closely associated with the moraines are channels which were evidently occupied by streams marginal to the ice lobes. Besides being too large for streams now occupying them, and being very often in positions where drainage could not exist without some barrier, now gone, the channels are peculiar in a variety of ways.

Often the channels begin and end abruptly, their continuation doubtless having been on the ice, and at times they terminate in gravelly deposits built of debris which streams brought through these valleys.

The drainage channel associated with the kame terrace on the south side of Moraine Stream, together with those associated with morainic ridges in the interfluve area between the left and right tributaries of Foggy River, are less than 100 metres long, ten to fifteen metres wide and two to three metres deep. Usually such channels are cut into drift but some are known to be cut partially or wholly into bedrock.

A somewhat larger drainage channel associated with an older more extensive moraine, was carved into till-like material during the Woodstock Glacial Advance. This former marginal drainage channel is thought to have extended the length of a line of low foothills immediately behind the Brooksdale Homestead, along which traces of morainic till can be found. The position of this former channel is now occupied by the Brooksdale Stream, the upper reaches of which once

Fig 3.2 View of a series of diagonally descending terrace levels (arrow) radiating, fan shaped, from a former lateral-terminal moraine. Foggy River is in the immediate foreground and the Kowai River is to the left of the picture.

formed an extensive swamp that has since been drained.

The dimensions of this channel approximate two kilometres in length by 300 metres at its widest part.

(4) Annavale and Benmore Surfaces

The highest and steepest surfaces, generally accepted as being the oldest known surfaces that can be attributed to aggradational processes in the Kowai Valley, are found as isolated remnants plastered along the valley sides. Both these surfaces are situated on the down valley side of bedrock buttresses that jut out from the valley walls. (Fig 3.3 and Fig 3.4.)

The preservation of these surfaces is due either to:

(a) their accumulation on the downvalley side and hence protection from erosion by the bedrock,

or (b) post depositional fault movement that resulted in the uplifting of these surfaces.

The latter explanation could account for the steepness, isolated and discontinuous nature of the Annavale and Benmore Surfaces, in view of the fact that each lies in close proximity to a suspected fault line. This is substantiated in that neither surface can be traced headwards. (Profile I.)

The easiest explanation, however, is that erosion moulded the surface topography of these surfaces during the long Woodstock-Otarama interglacial, (Fig. 3.1), the reason being that each surface is underlain by weathered gravels of Woodstock age and capped by a thick loess deposit some two to three metres thick. Neither deposit has been disturbed or replaced by deposits of a younger episode of glaciation.

The textural nature of the material beneath the Annavale surface is unknown but is suspected of having the appearance of glacial till while that beneath the Benmore Surface is very till-like in appearance. The presence of chert within the material comprising the Benmore Surface ~~discounts~~ discount the possibility that the origin of this material is from the Brooksdale Catchment.

The morphology and nature of the material comprising the Benmore Surface may indicate that this is all that remains of a lateral moraine of Woodstock age, that extended the length of a line of foothills flanking the left bank of Brooksdale Stream to include the Brooksdale Surface. Along this section of the valley Woodstock deposits are overlain by younger outwash gravels of Otarama age.

A bench cut into the right flank of the Benmore Surface by the Kowai River consists of a thin veneer of a grey outwash gravel deposit, directly overlying the Woodstock till.

Along the left flank of the Benmore Surface a broad trench thought to have been cut by (1) meltwater draining along a lateral channel and (2) drainage from the Brooksdale Catchment, is today occupied by an undersized stream and swamp.

A barrier of aggradational outwash gravel deposited across the toe of the Benmore Surface during the Blackwater glacial period, blocked off the drainage from this channel to form a lake. Subsequent erosion of this barrier resulted in the drainage of this lake. The floor of this channel is now part pasture and part swamp that has developed upon a thin veneer of post glacial deposits.

(5) Springfield Mound

An elongated mound 4.5 kilometres to the east of the Annavale Surface protrudes some ten or so metres above the Kowai Pastures Surface. (Fig 3.5.) This mound consists of a gravel deposit thought to be of Woodstock age, the texture of which suggests that it may in part be till. The size of the boulders comprising this mound indicates that it may have been close to the terminal moraine of the Woodstock glacier which in turn suggests that perhaps the Annavale Surface is a remnant of the Woodstock glacier terminal moraine or part of a recessional moraine. Similarly the Benmore surface could possibly be a remnant recessional moraine.

Fig 3.3 View of the Annavale Surface (arrow), rising steeply above the Kowai Pastures Surface (foreground).

Fig 3.4 The Benmore Surface (arrow) abutting against a bedrock outcrop.
The Kowai Surface is in the foreground.
The Kowai River flows from left to right between the two surfaces.

(6) <u>Ayrdale Surface</u>

The Ayrdale Surface lies to the immediate south of the township of Springfield and consists of a deposit of glacial outwash gravel of Woodstock age. This surface persists from the vicinity of Trig E 434m (1425') south eastwards, across Domain Road before merging with a recently formed surface of Post Glacial age. (Profile I.)

(7) <u>Caesars Hill Surface</u>

This surface consists of a series of ridges and mounds stretching between the Rubicon and Little Kowai Rivers in the vicinity of 'Torby Cottage' and to the east of a low bedrock ridge that strikes towards the north east within this interfluve area. (Profile I.)

The material comprising this surface consists of a till-like material of Woodstock age overlain by a loess deposit equivalent in thickness to that on the Annavale and Benmore Surfaces. These deposits encircle an area of low lying swamp, the drainage channel for which drains into the Rubicon River. A section at this locality reveals a great thickness of peat which has been dated at 14,100 $\pm$ 240 years (Moar and Gage, 1971) and 12,750 $\pm$ 210 years (Moar and Gage, 1972).

This unusual looking morphological feature is thought to represent a period of still-stand of the

Fig 3.5 Springfield Mound (arrow) rising above the level of the Kowai Pastures Surface (foreground).

Woodstock ice. (Fig 3.6.) The direction of ice flow appears to have been from the Kowai River as there is no evidence that the upper reaches of either the Rubicon or Little Kowai Rivers were glaciated subsequent to the Avoca Glaciation.

It is thought, therefore, that the ice mass from the Kowai River crossed the eastern end of the low foothill ridge, immediately behind the Brooksdale Homestead to spread out across the Rubicon River and flow along the base of Caesars Hill into the Little Kowai River, thereby forming an eddy between two ice flows.

A very limited deposit of Woodstock till-like material directly across the Little Kowai River from the large area of swamp lying at the foot of Caesars Hill (Fig 3.7) confirms the possibility that Woodstock ice occupied this section of the Catchment. Several mounds of Woodstock gravel lying at the southern margin of this swamp, within the Rubicon River Valley, also confirms the existence of Woodstock ice at this locality.

Numerous outcrops of Woodstock till-like material can be found plastered along the lower reaches of the foothills lying to the west and north-west of Kowai Bush settlement to indicate that the Woodstock Glacier completely occupied the lower reaches of the Kowai Valley.

Fig 3.6 Caesar's Hill Surface lying between the Rubicon and Little Kowai Rivers in the vicinity of 'Torby Cottage'. The smooth ridges in the background and to the right of the photograph are composed of Woodstock gravel.

Fig 3.7 Area of swamp at base of Caesar's Hill, showing possible direction of flow of the Woodstock ice. View taken from Little Kowai River looking towards the Russell Range.

(8) Mount Torlesse Surface

From the eastern margin of the Mount Caesar Surface the Mount Torlesse Surface slopes steeply towards the Little Kowai River. (Profile I.)

The materials comprising this surface occupy the interfluve area between the Rubicon and Little Kowai Rivers and merge with deposits of an equivalent age that issued from the Waimakariri River. Numerous river sections show great thicknesses of Otarama Outwash gravel capped by a considerable deposit of loess a metre or two thick. Other sections, however, show an additional horizon of younger outwash gravels deposited upon the Otarama gravels. These are of Blackwater I age and are capped by a loess deposit of variable thickness generally in the order of 0.5m to 1m. The source of the Blackwater I gravels appears to be from the Waimakariri River. They form a wedge shaped deposit that thickens towards Otarama Station.

(9) Kowai Pastures Surface

This, the most extensive of all the surfaces, stretches from the bridge adjacent to the type section, eastwards to the Waimakariri River and south eastwards beyond the boundary of this study area. (Profile I.)

Eastwards of Springfield, exposed sections along the banks of the Waimakariri and Lower Kowai Rivers show sequences approximately 100 metres thick of outwash gravel of Otarama age capped by a deposit of loess some one to two metres thick. The Kowai Pastures Surface in the vicinity of the township of Springfield lay beyond the reach of Blackwater I gravels that issued from the Waimakariri River. However, evidence exists to show that portions of the Kowai Pastures Surface further towards the west were affected by both erosional and aggradational processes, at this level during Blackwater I times, by the Kowai River itself. A farm track cutting along the right bank of the Kowai River, approximately 100 metres downstream from the West Coast Rail Bridge descends from the Kowai Pastures Surface to several lower terrace levels. Here we can see (Fig 3.8) a thick sequence of Otarama outwash gravels capped by a loess deposit approximately 1.5 metres thick. The original thickness of this loess deposit must have been considerable for much of it would have been eroded away prior to the deposition of a further sequence of outwash gravels of Blackwater I age. This latter gravel deposit is succeeded by another loess deposit, the top of which forms the present day Kowai Pastures Surface.

A second locality, the type section, (Fig 3.9) indicates that aggradational processes still operated in this locality well into post-glacial times. Here, a considerable thickness of Otarama and Blackwater outwash gravels have been removed. A channel deposit of post glacial fluvial gravels directly overly Otarama

Fig 3.8 Kowai River cutting showing the sequence of deposits underlying the Kowai Pastures Surface. Horizontal arrow shows the loess deposit overlying Otarama Outwash gravels. Blackwater gravels overly the Otarama loess and are in turn overlain by Blackwater I loess. The vertical arrow indicates the contact between Blackwater I outwash gravel and loess.

Fig 3.9 View of the type section showing deposits that represent three phases of aggradation. The basal (orange) unit consists of Woodstock outwash gravels. The upper (grey) unit is a channel deposit of post glacial gravels. One edge of this channel is indicated by the arrow.

outwash gravels. The channel is outlined by

(1) the difference in degree of weathering between the Otarama and post-glacial gravels deposits,

(2) the difference in the degree of compaction between the two units, and

(3) the thickness of the overlying loess deposit. Adjacent to the road cutting through this section, Otarama gravels persist to the top of the sequence and are capped by a deposit of loess approximately one metre thick. Elsewhere along this same section the loess covering over the post-glacial channel deposit is only fifty or so centimetres thick. (Fig 3.9.)

This post glacial river channel can be traced eastwards along the base of Russell Range beyond Springfield and on towards the Hawkins River. It is believed that this channel drained small streams from the Russell Range, possibly including Thirteen Mile Bush Stream, into the Hawkins River. Headward erosion and lateral migration of the Kowai River eventually captured this drainage system.

The size of the former channel suggests that it was too small to have drained the entire Kowai River into the Hawkins River.

(10) Kowai Surface

This too is an extensive surface stretching from the gorge section of the Kowai River below the junction between the West Branch Kowai and Kowai Rivers, downstream to the junction of the Rubicon and Kowai Rivers. (Profile I.)

The Surface results from extensive erosion, during Late Blackwater times, of the Otarama gravels, followed by several phases of aggradation during which this surface built up to almost its former level. (Fig. 3.10.)

The deposits underlying the Kowai Surface are not sufficiently weathered to be of Otarama age, nor are they sufficiently fresh in appearance to be of Post Glacial Age. However, channels of post glacial gravel do cut across this Surface in several localities.

At least two units of gravel are recognisable. Their volume and clay mineralogy indicate that these deposits are older than post-glacial gravels. Similarly the thickness of the loess covering is intermediate between the thicknesses of loess deposits overlying Otarama deposits on one hand and post-glacial deposits on the other. The most accessible exposures are to be found along the left bank of the Kowai River, one hundred metres upstream from the junction of Brooksdale Stream and the Kowai River. Other sections of interest include a deposit of grey coloured silt and clay sized material containing a considerable amount of vegetative matter. Portions of trees are also to be found underlying the Kowai Surface in an exposure of the Kowai River opposite the junction of Thirteen Mile Bush Stream and the Kowai River.

From the aerial photographs the drainage pattern during the final stages of aggradation is clearly seen. During this time the Kowai River flowed in a line diagonally across its present path along a line drawn between the Benmore and Brooksdale Homesteads.

The drainage direction however, was deflected by the higher left bank of the Rubicon River to flow in the direction of the present Rubicon River. The Kowai Surface therefore never attained the height of the Mount Torlesse Surface during this period of aggradation. This period of aggradation was superceded by the final period of degradation that has continued to the present day and was accompanied by a gradual lateral shifting in the course of the Kowai River from the left side of the Kowai Valley to its present position. This period of degradation is marked by a series of terrace levels incised below the level of the Kowai Surface, along the length of the Kowai River.

The lateral migration of the Kowai River eventually lead to the capture of the drainage system that once flowed from the Kowai Valley across the Kowai Pastures Surface and into the Hawkins River. Despite the amount of vertical erosion that has taken

Fig 3.10 View of the Kowai Valley showing the extensive nature of the Kowai Surface (green). The Valley in the background is Thirteen Mile Bush Stream.

place along the Kowai River, water flowing along a natural gradient is today channelled from the present day river bed along the Kowai Pastures surface for irrigation purposes. It appears therefore, that although there were undoubtedly phases of degradation throughout the Late Pleistocene, the majority of terrace levels exhibiting the greatest amount of vertical separation along the lower reaches of the Kowai Valley, have been the result of very recent erosion by the Kowai River in response to the rate of downcutting exhibited by the Waimakariri River. As such the Kowai River has, and still is, undergoing a period of degradation by the headward erosion of its river course in order to establish an equilibrium of flow, between its headwaters and the Waimakariri River.

On the completion of the mapping and surveying of terrace surfaces, an attempt was made to trace, as far as possible, the glacial deposits for the various glacial advances represented within this Catchment.

The following section presents the conclusions in the form of a detailed chronological account of the glacial advances, their maximum extent and the locality and physical characteristics of the deposits themselves.

V STRATIGRAPHY AND HISTORY OF THE LATE PLEISTOCENE DEPOSITS

(1) Avoca Glaciation

(a) Name. The name relates to the location of the thickest surviving deposits from this glaciation beneath an undulating plateau, rising to between 793m (2600') and 976m (3200') east of Avoca (Gage, 1958).

(b) Ice Extent. At the maximum of the glaciation, ice filled the entire Waimakariri Catchment, including Castle Hill Basin. As asserted by Haast (1879, p. 392) and more diffidently by Speight (1935, p. 309), the Waimakariri and Rakaia Glacier systems were joined by transfluence through Coleridge Pass and Lake Lyndon Saddle, and they may also have coalesced in the piedmont area south-east of the Malvern Hills. All the main valleys of the Kowai Catchment were probably filled by interconnecting ice, through which only the Torlesse Range protruded. The Avoca ice discharge gap is clearly seen from viewpoints on the Canterbury Plains near Springfield. Avoca ice over-rode and planed the foothill summits and ridges within the Kowai, West Branch Kowai, Rubicon and Little Kowai Catchments; the lower flanks of the Malvern Hills and reached beyond Sheffield. Its farthest limits are unknown.

(c) Deposits. No deposits that could be attributed to the Avoca Glacial advance exist within the Kowai Catchment. Deeply weathered, loess covered gravels are found on terraces and at the end of spurs around the base of the Malvern Hills. These gravels, together with the morainic gravels of Racecourse Hill and Sheffield Mound (Hutton, 1884, pp 449-54; Speight, 1928, map; 1938, pp 154-56) are considered to be the remains of a former outwash sheet joining with similar outwash deposits from other valleys to form a piedmont alluvial plain analogous with the Canterbury Plains. From their elevation, these deposits are of Pre-Woodstock age, and were most probably formed during the Avoca Glaciation (Gage, 1958).

Further up the Hawkins Valley, on the spurs of the Black Hills, there are coarse breccias possibly attributable to glaciation. These deposits, if of glacial origin, might be attributed to the Waimakariri glacier if it had reached as far as Racecourse Hill, and even if it had reached Sheffield, but it is also reasonable to credit them to a distributory of the Rakaia glacier which came down the Upper Selwyn Valley across a low divide and past the Dalethorpe Homestead.

> "I can see no difficulty in this explanation, and it is certainly as satisfactory as to attribute the deposits to the former extended Waimakariri Glacier. All the same, the conclusion that these deposits are glacial is based only on the shape, size and position of the boulders, unsupported by other evidence and so I cannot view it as entirely convincing. No doubt large rivers issuing from the face of the old ancient glacier have swept away a good deal of the old moraines and have left remnants, so that perhaps the absence of other evidence, such as the occurrence of crescentic heaps of angular material across the old front of the glacier, &c; is not so remarkable - in fact, it is what might have been expected." (Speight, 1928.)

(2) Woodstock Advance

(a) Name. The name is taken from Woodstock Station at the lower end of the Staircase Gorge (Gage, 1958).

(b) Ice Extent. The maximum extent of Woodstock ice is uncertain. There is no evidence that it reached beyond the Springfield area or that it occupied Castle Hill Basin (Gage, 1958).

Ice from the Rakaia Glacier penetrated the Acheron Valley and invaded the head of the basin of the West Branch Kowai, a Tributary of the Kowai rising just south of Porters Pass across a low divide, in the vicinity of Rabbit Hill 1198m (3929'). Some of the features within the upper part of the basin can be attributed to ice action.

> "In the middle of the basin there are numerous large blocks of Greywacke scattered over the surface, which suggest from their size that they have been carried by ice; but there is a possibility - perhaps a remote one - that they have been shed from the slopes of Benmore at a time antecedent to the dissection of the weak Cretaceous beds on which they now lie, and it is just possible, though not probable, that they have been transported by agencies other than ice." (Speight, 1924.)

There is undoubted proof of the presence of glacier ice lower down the Rakaia Valley having crossed ridges at a higher elevation than this divide. For this reason it also seems likely that ice at this time crossed Porter's Pass divide to penetrate the Kowai Valley.

This advance is not delineated by a recognisable terminal moraine system. However, because Woodstock deposits are found beyond the moraines of later advances, it is evident that in this area as elsewhere, the Woodstock was the greatest known advance of the Late Pleistocene.

(c) Deposits. Till-like deposits are to be found plastered along the left banks of the Brooksdale Stream and Little Kowai River and underly such totpographical features as the Benmore, Brooksdale and Caesar's Hill Surfaces (Map). Although unproven, till-like deposits are thought to lie beneath the Annavale Surface also. These surfaces are considered to be morainic remnants of the receeding Woodstock Glacier. A suspected till of uncertain age, but possibly belonging to the Woodstock Glacial Advance on account of the degree of weathering and elevation of the deposit, is to be found as a thin veneer upon Gingerbread Spur - an ice-planed bedrock ridge within the Torlesse Stream Catchment. (Profile II.) The source of this till is the Kowai Catchment as large angular blocks of red and green chert are prominent constituents of this till. Outcrops of chert bedrock flank the western slopes of Mount Torlesse. No bedrock outcrops of chert are to be found within the upper catchment of Torlesse Stream. No trace of Woodstock deposits, can be found within the West Branch Kowai or Thirteen Mile Bush Stream Catchments.

At numerous localities along the lower reaches of the Kowai, Rubicon and Little Kowai Rivers there are small outcrops of outwash gravel of limited extent and unknown thickness. These glacial deposits are the oldest known within the entire study area and form the basal unit for the extensive aggradational sequence of deposits to be found in this part of the Kowai Valley. These deposits consist of coarse, poorly sorted, orange-brown, oxidised gravels set within a matrix of silts sands and a very considerable proportion of clay sized material.

A thin deposit of deeply weathered, angular but fine grained slope deposits overly the basal deposit of outwash gravel at the type locality and represents the period of surficial bedrock weathering during the long Woodstock-Otarama interglacial. Evidence for continuity is in most places obscured by deposits of noticeably fresher gravels deposited upon benches carved into material of Woodstock age. This scant survival of Woodstock deposits is consistent with the view that the subsequent Otarama Advance reached almost as far as and attained almost the thickness of the Woodstock ice.

(3) <u>Otarama Advance</u>

(a) <u>Name</u>. The name is from 'Otarama Station' near the township of Kowai Bush.

(b) Ice extent. It is not clear whether the thickness of ice during Otarama times within the Acheron Valley and Lake Lyndon area was sufficient to top Rabbit Hill, as was the case during the previous Woodstock Advance.

The small nature and limited extent of the moraine at the head of the West Branch Kowai River together with the fact that this deposit does not appear to be as weathered as deposits of known Woodstock till found in other parts of the Kowai Valley, tend to favour the possibility that this deposit is of Otarama age. To substantiate this further, the moraine appears to grade into surfaces within the upper part of the valley but are too high to grade into the Blackwater I Surfaces lining the lower portion of this valley.

The Otarama deposits within the Kowai Valley, therefore, probably originated within the Kowai Valley itself and extended down valley to coalesce with a lateral glacier from the Foggy River Catchment. This mass of ice penetrated down valley to the junction of the West Branch Kowai and Kowai Rivers, where the maximum extent of ice advance is delineated by what is considered to be the terminal moraine of the Otarama Glacier. (Fig 3.11.)

(c) Deposits. Exposures of Otarama till can be found lining the right bank of the Kowai River along that section between the junction of the Kowai and

Torlesse Stream, down valley to the Foggy River confluence where all trace of this deposit is lost, due to truncation along an active fault crush zone. (Fig 3.12.)

The uppermost terrace at Otarama, near Kowai Bush is underlain by about 60 metres of comparatively fresh, subrounded to rounded greywacke gravels resting unconformably on an irregular surface eroded from Woodstock gravels and older formations. In this area the upper 7 metres is composed of very coarse unstratified and unsorted morainic gravels, including subangular blocks up to 3 metres in diameter, grading laterally into glaciofluvial gravels containing isolated large morainic blocks deposited by Otarama ice issuing from the Waimakariri River.

The presence of similar ice-borne erratics along the high gravel bank in the angle between the Kowai and Waimakariri Rivers was noted by Hutton in 1883 and later confirmed by Speight in 1938.

> ". . . an accumulation of angular masses up to 6ft by 4ft by 3ft in size with a large number of smaller sizes with angular and rounded edges lies at the base of the terrace, in the angle between the rivers, and one especially massive boulder, 10ft by 10ft by 12ft, with edges well rounded, lies near the top of the terrace surrounded by others of smaller size." (Speight, 1938.)

The extensive nature of the terrace remnants and the great spread and thickness of Otarama outwash gravel requires that the discharge of glacial debris by

Fig 3.11 Junction of the Kowai River (centre) and West Branch Kowai (left). The arrow indicates the position of what is considered to be a remnant of the Otarama terminal moraine.

Fig 3.12 Exposure of Otarama till lining the right bank of the Kowai River between the Torlesse Research Station and Foggy River.

meltwater torrents continued for a considerable period of time but that during the post Otarama Recession with the retreat of ice from the Otarama maximum, the deposits from this advance were eroded and reduced almost to their present extent.

Eastwards from the Kowai Bush area, the upper surface of Otarama gravels becomes the apical portion of the Waimakariri segment of the coalescing alluvial fans forming the Canterbury Plains which is 387 metres above mean sea level and 98 metres above the level of the Waimakariri River. Westwards the deposits of Otarama outwash gravel thin rapidly towards the terminal moraine. At many localities these deposits have been eroded away completely while at others, including the type section, Otarama outwash gravels aggraded upon Woodstock deposits, and were subsequently eroded and reduced to a horizon a mere 6 metres or so thick. The characteristic textural features of these gravels include the rounded to subrounded, relatively fresh greywacke boulders set in a matrix of sand silt and appreciable clay, the colour of which is a dark pink-brown. Overall the unit is very compact. Otarama deposits are appreciably more weathered than deposits of the younger Blackwater advances, however, the difference is only visible where the two deposits are seen together.

(4) Blackwater Advance

(a) Name. The name is derived from Lake Blackwater which lies amidst extensive moraines and outwash (Gage, 1958).

(b) Ice Extent. The Blackwater deposits record two distinct advances separated by a brief recession and followed by intermittent withdrawal interrupted by one or more temporary re-advances.

In distribution the moraines seem at first sight to be in almost inextricable confusion. This is due to the fact that during a general stand the ice lobes halted at several successive levels in a region of marked topographic irregularity. At certain levels some of the hills rose as nunataks above the ice, and lateral tongues extended from the major ice lobes into the minor valleys.

In form there is marked variety including kame topography, single moraine ridges, groups of moraine ridges, moraine terraces and drainage channels.

Within the interfluve area between the True Right Kowai River and Moraine Stream, a massive build up of till, extending from the mouth of Moraine Stream headwards to the Kowai River - John's Stream junction, represents ice fronts of the several stands during Blackwater I, II and Poulter Glacial Advances (Fig. 3.13 and Profile III).

It is possible that ice from the Blackwater I Glacial Advance issued solely from the True Right Kowai River, to occupy the entire area between the True Right Kowai River and Moraine Stream. This ice deposited a great thickness of till; into which subsequent erosion by meltwater during the recession of Blackwater Ice, carved two separate drainage basins. In the event of this explanation being true, the central and highest morainic ridge in this interfluve area is not strictly a medial moraine.

However it is also possible that during the Blackwater I Glacial Advance two independent ice masses issuing from the True Right Kowai River and Moraine Stream respectively, merged into a single ice flow, within this present day interfluve area, that extended downstream to the junction of the True Left and True Right Kowai Rivers where a deposit of very bouldery till marks the maximum extent of this glacial advance.

One factor that favours the second explanation is that during the subsequent Blackwater II Glacial Advance the Moraine Stream Catchment was sufficiently large to supply enough ice to form an independent ice lobe within its own valley. It therefore follows that during previous glacial advances two glaciers emerged from independent cirques on the eastern side of the Torlesse Range. The only difference between the Blackwater II Glacial Advance and those advances prior to it, is that the extent and thickness of the

Fig 3.13 The Morainic System between the Kowai River (bottom right) and Moraine Stream (top right to bottom left). The kame terrace is to the left of Moraine Stream (vertical arrow).

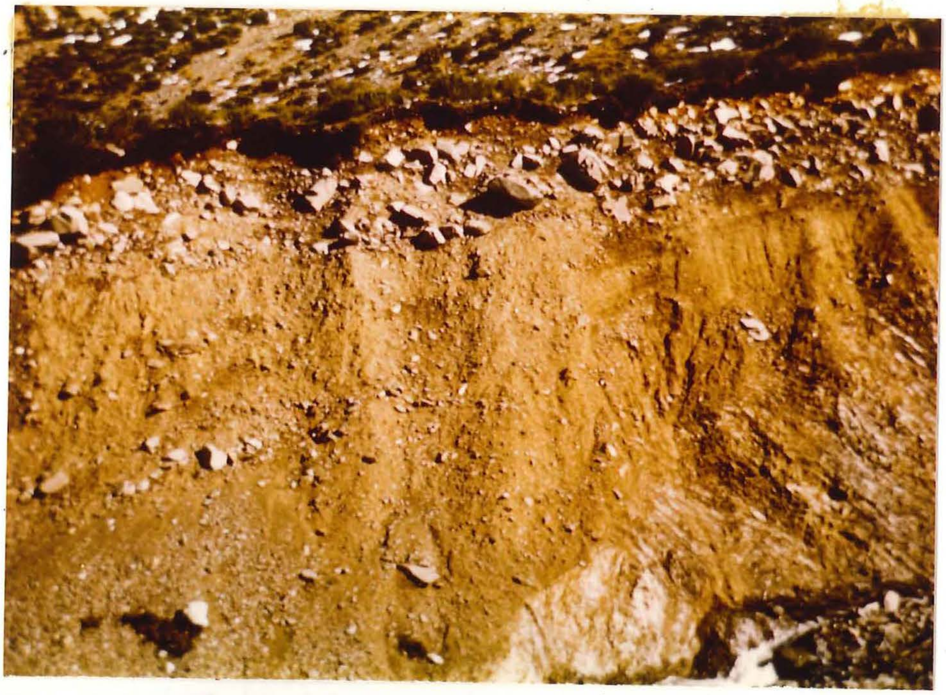


Fig 3.14 An example of the till deposits to be found within the Kowai and Moraine Stream Catchments.

ice during the earlier advances was sufficient for the glaciers to over-ride any intervening bedrock barriers, to merge and form a single iceflow. In this case the central morainic ridge is a remnant medial moraine.

An ice lobe of the Blackwater I Glacial Advance extended along the True Left Kowai River to reach its terminal position at the junction of the True Left and True Right Kowai Rivers.

Within the Foggy River Catchment two ice lobes of the Blackwater I Glacial Advance penetrated down valley, from independent cirques, to merge at the junction of the left and right tributaries. The maximum extent of this advance is uncertain. Within this catchment, however, the presence of large morainic boulders lining the valley walls and within the present day river course, delineate the terminal moraine as being approximately mid-way between the junction of the left and right tributaries of the Foggy River and the Kowai River - Foggy River confluence.

The Blackwater II Glacial Advance is marked by the presence of lateral moraines flanking the central medial moraine within Moraine Stream and True Right Kowai River.

Within the Moraine Stream Valley a Blackwater II lateral moraine is preserved on the left bank while on the opposite bank a steeply plunging kame terrace and associated drainage channel mark the maximum extent of this advance as being within this valley.

Within the True Right Kowai River a series of degradational terrace levels partly cut into bedrock and partly through glacial drift is all that remains of the Blackwater II lateral moraine. These flank the right bank immediately below John's Stream.

The terminal moraine for the Blackwater II Glacial Advance within the True Left Kowai River is marked by a small deposit of till at the junction of this river and a small unnamed tributary draining the slope behind Chert Stream.

The interfluve area between the two tributaries of Foggy River marks the site of the maximum extent of the Blackwater II Glacier. Several arcuate moraine ridges can be seen flanking the sides of these tributary valleys at this locality.

(c) <u>Deposits</u>. In composition the moraines contain clay, silt, sand and gravel sized materials in almost every conceivable proportion. The largest boulders, approximately one to two metres in diameter are smaller and fewer in number than in till deposits of the older and more extensive glacial advances, hence, the overall size range of material comprising the younger tills tends to be of a finer grade.

There is no significant difference in the degree of weathering between tills or outwash gravel deposits of Blackwater I and II advances. The tills are generally subangular to angular, unsorted, compact units containing a substantial proportion of silt sand and clay sized material, the colour of which can vary from yellow-brown to red-brown to khaki. (Fig 3.14.) Outwash gravels of equivalent age are composed of fresh grey coloured gravels set in a loose friable sandy textured deposit that contains substantially less clay sized material than till of equivalent age. The deposits of outwash gravel vary in thickness throughout the catchment, but all are poorly sorted and sometimes show rough stratification. (Fig 3.15.)

(5) Poulter Advance.

(a) Name.

"The name Poulter Advance is given to the final major ice advance, which deposited impressive mounds of terminal moraine in the main Waimakariri Valley near the mouth of the Poulter River." (Gage, 1958.)

(b) Ice Extent. The youngest of the four principal advances recorded in the Kowai Valley is the Poulter, characterised by bold-fronted little eroded moraines fronted by discontinuous outwash terrace surfaces of limited extent.

The moraines themselves are small in comparison with those of previous advances and are to be found within larger and more extensive moraines of the Blackwater II Glacial Advance. The best preserved

Fig 3.15 Typical outwash gravel flooring the Kowai River Valley.

can be found along the left bank of Moraine Stream, and in the interfluve area between the right and left tributaries of Foggy River. An impressive mound of Poulter till at the mouth of John's Stream is associated with a series of short, steeply dipping degradational terrace levels cut into Blackwater till, by meltwater released during the recession of Poulter ice. A rapid ice advance of short duration could account for the meagre extent of deposits from the Poulter maximum. Blackwater deposits were not seriously threatened by erosion or burial during the Poulter Advance which amounted to a glaciation of smaller magnitude than the Blackwater Advances.

(c) Deposits. Poulter glacial deposits are characterised by slightly weathered, grey coloured gravels set in a loosely textured groundmass of mainly sand and silt with a lesser abundance of clay sized material than in the tills of the older advances. Their bouldery nature is apparently due to the relatively short distance the material has been transported.

Outwash gravels of equivalent age are of a similar colour and degree of weathering but differ in texture and friability due to the almost complete absence of clay sized material. Hence, the deposits are generally very bouldery, loose, friable and open textured.

Poulter surfaces are characterised by protruding boulders, thin loess cover, general lack of erosional defacement of original detail and their occurrence down to present river level.

(6) <u>Post Glacial Fluvial Deposits</u>.

Within the upper reaches of the Kowai Catchment where the processes operating throughout the Pleistocene Epoch have been essentially degradational, post glacial fluvial gravels have been restricted to within the incised river channel that has remained relatively stable since post-Blackwater Glacial Advances.

These deposits consist of sandy gravel with little to no clay sized fraction, hence they are loose and friable. The boulder sized material that comprises the bulk of these deposits is grey in colour and shows no sign of weathering. Nowhere is there a great thickness of these deposits to be found. Within the lower Catchment, however, a different picture can be seen, due to the aggradational nature of the depositional processes that have operated in these reaches throughout the Lake Pleistocene. Here, post glacial fluvial gravels, though limited in extent and thickness, are to be found as a thin veneer upon all but the Woodstock outwash surfaces.

The most noticeable deposit of post glacial gravels can be seen in the form of a channel deposit cut into the Kowai Pastures surface. This channel extends from the type section to the Hawkins River and until very recently drained the 13 mile Bush Stream and several minor streams from the Russell Range before being captured by the Kowai River drainage.

VI DIRECTION OF ICE MOTION

The substantial relief of the region, coupled with the gradual change from mountain terrain eastward to plains, strongly influenced the forms and direction of ice motion of the Pleistocene glaciers. The earlier glaciers were probably broad bodies flowing gently down towards their eastern termini. In the upper reaches an interconnected system of glaciers grew so thick that they coalesced and covered all but the highest part of the Torlesse Range, as is evidenced by the ice planed foothill ridges and summits, including Papanui Road, between the Waimakariri and Rakaia Glacial Systems. These features have been attributed to the Avoca Glacial Advance (Fig 3.16). Nearly all of these planed ridges slope quite noticeably towards the east and north east, thereby possibly indicating the dominant direction of ice motion at this time. A linear surface along the Russell Range trends to the north east and may reflect the trend of the ice in this

Fig 3.16 Ice-planed summit between Joyce's and Fault Streams. The surface slopes towards the north-east.

Fig 3.17 View looking south east from the headwaters of Fault Stream. Ice-planed summit in foreground, eastern end of Russell Range in background showing N-E trending linear surface (arrow) and the Kowai Valley in between.

part of the region. (Fig 3.17) However, this surface may also be of tectonic origin. Later advances were narrow valley glaciers emerging from steep mountain valleys on to the plains where they spread out in piedmont fashion.

In general, the direction of early ice motion in these valleys cannot now be determined, since the records were erased by the later stands. However, along a number of valleys it is possible to pass from one drainage channel to another through what are here called 'through valleys', that is, valleys connected across lowered divides. Accompanying this condition there has been much diversion of drainage across the lowered divides, so that is very frequently the case that the present divide does not coincide with an earlier position.

A 'through valley' across a divide separating Moraine Stream from Gorge Stream carried ice during the Woodstock, and possibly during the Otarama glacial advances, in a south to SSW direction from the upper reaches of the True Right Kowai Catchment along the eastern flank of the Torlesse Range.

Simultaneously, another ice flow in a similar direction from the upper reaches of the True Left Kowai Catchment flowed across a low divide separating the True Left Kowai from the True Right Kowai Rivers. Then flowed south-eastwards spreading out across what is now the main drainage valley, across a second divide of bedrock and on into the Torlesse Stream Catchment, whereupon, the direction of flow was deflected by the Papanui Road Range towards the southwest along the present Kowai River Valley.

A veneer of weathered till deposited during the Woodstock Glacial Advance, along the summit of an ice planed bedrock ridge within the Torlesse Stream Catchment (here called 'Gingerbread Spur') contains large angular boulders of chert the source of which is probably the upper reaches of the Kowai River. During the Blackwater I Glacial Advance down cutting deflected the ice motion down what is now the major current drainage direction. Evidence for such a change can be found in the form of a kame terrace and its associated drainage channel, of Blackwater Glacial Advance age, within Moraine Stream. The former drainage outlet into Gorge Stream was abandoned in favour of an easterly outflow direction along what was to develop into the present day drainage channel. Small valley glaciers flowed down these existing stream valleys, from all the well developed cirques, during the Blackwater and Poulter Glacial Advances.

Because the ridge crests did not greatly exceed the minimum elevation that was necessary for the formation of alpine glaciers and erosion of cirques during Late Pleistocene times, coupled with the fact that catchment areas were limited by the narrowness of the divides and the steep gradients of gulches draining the divide, the glacial erosion forms were neither large nor extensive and preservation has been poor. In part, former depositional landforms have been flushed out by post glacial streams or buried by later outwash gravel, talus and colluvial debris.

CHAPTER FOUR

LATE PLEISTOCENE FAULTING

I PORTER'S PASS FAULT ZONE

The New Zealand Geological Map 1:250,000, Sheet 18, Hurunui, 1st Edition; of the N.Z.G.S. Series shows a single major fault trace striking NE-SW from the vicinity of Joyce's Stream across the headwater region of the Little Kowai, Rubicon and Kowai Rivers, through Porter's Pass and on into the Rakaia Catchment in the vicinity of Lake Coleridge. This fault has been named the Porter's Pass Fault.

Closer investigation has revealed a substantial fault zone, bordered along the western margin by a series of isolated outcrops of fault crushed bedrock and recent fault scarplets, for which the name of Porter's Pass fault has been retained. A second fault trace delineated by a series of isolated outcrops of slickensided bedrock with associated fault Pug, together with a very pronounced fault contact between Torlesse bedrock and Tertiary marine sediments, is referred to in this report as the 'Benmore Fault'. As early as 1924 Speight commented that -

> "It is probable that the gap between the Big Ben Range and Mount Torlesse, through which passes the West Coast Road over Porter's Pass, has been determined by faulting."

This zone of faulting will be referred to as 'The Porter's Pass Fault Zone' within which, the main topographical features appear to have arisen from fault movements which have affected a peneplain formed of Triassic-Jurassic rocks. While attributing the major outstanding features of the area to faulting, it should be noted that the deformational movements did not, in all cases result in rupture, but rather warping.

(1) Evidence for the Benmore Fault

A marked fault contact between bedrock and Tertiary marine sediments can be traced along the hillside that flanks the right bank of the West Branch Kowai River, from a low divide immediately below and to the right of Trig J 1198 m (3929') also called Rabbit Hill; to the junction of the Kowai and West Branch Kowai Rivers. (Fig 4.1.) This section of the Benmore fault is also outlined by an occasional break in slope along the hillside and one large slump feature. Together, these three lines of evidence clearly delineate the strike of the Benmore Fault. The dip of the fault plane in this locality is approximately 40° to the south-east, the bedrock having been thrust over the Tertiary

Deposits from the southeast. There is not sufficient evidence to determine the amount of throw and transcurrent movement.

A small exposure of crushed bedrock along the left bank of the West Branch Kowai River near its junction with the Kowai River, lies along the line of strike of the Benmore Fault. Further manifestations of this fault are to be found in the headwater area of Brooksdale Stream. These include vertical faces of bedrock, outcrops of fault pug and slickensided bedrock. A very straight tributary of Beech Tree Stream backs on to the Brooksdale Stream Catchment, the former draining along the base of what may be a fault scarp along its right bank. An isolated outcrop of slickensided bedrock can be found in the Beech Tree Stream riverbed.

No sign of this fault could be found between the Rubicon and Little Kowai Rivers.

The left bank of Fault Stream is a fault-plane. A recent fault scarplet can be traced headward up this stream and across a low divide into the upper reaches of Joyce's Stream. (Fig 4.2) This scarplet is quite pronounced and easily traced in an easterly direction, (Fig 4.3) towards an aggradational outwash surface near Otarama below which, the trace dives. (Fig 4.4.) A small section of exposed fault-plane can be seen 100 metres upstream from the railway viaduct across Joyce's Stream.

Fig 4.1 View looking down West Branch Kowai Valley from the saddle below Rabbit Hill. The trace of the fault is indicated by the arrow.

Fig 4.2 A small scarplet along the Benmore Fault. Fault Stream is on the other side of the low divide. Joyce's Stream is on this side of the divide.

Fig 4.3 Section of Benmore Fault within Joyce's Stream Catchment, looking towards same divide as in previous photograph. Fault scarp is indicated by arrow.

Fig 4.4 View showing the Benmore Fault diving beneath an aggradational outwash terrace surface near Otarama. Joyce's Stream is to the right of the figure. The Waimakariri River is in the background.

It is possible that an extension of this fault trace could correspond with the break in slope along a straight section of terrace that extends along the left bank of the Waimakariri River, immediately below the gorge in the vicinity of Otarama. This terrace edge corresponds to the division between glacial outwash deposits of Woodstock and Otarama ages, as shown on the New Zealand Geological Map 1:250,000, Sheet 18, Hurunui, 1st Edition of the N.Z.G.S. Series.

The state of preservation of this scarplet in Joyce's Stream indicates that it is a relatively recent event, movement along which displaced the initial fault plane. At one time this fault plane was a continuous surface along the length of the left bank of Fault Stream and the right bank of the main tributary of Joyce's Stream. Both sections of this displaced plane strike to the NE.

(2) Evidence for the Porter's Pass Fault

A series of recent well preserved fault scarplets can be traced along the hillside flanking the left bank of Lake Lyndon, towards the northeast, across the West Coast Highway at its highest point 930 m (3050'), and on along the hillside flanking the right bank of the Kowai River. (Fig 4.5.) These represent a line of active dextral shearing, which at the eastern end of Lake Coleridge disrupt several sequences of late glacial terraces.

Fig 4.5 Porters Pass fault runs from left to right across snow covered hillside (arrow). Fault scarplets are more easily seen in Fig 4.6. The triangular blocks of bedrock (vertical arrows) have been dislodged from the hillside behind and are thought to be synchronous with the large scale slumps.

Fig 4.6 Large scale slump feature. Scarplets of the Porter's Pass Fault can be seen on the skyline (arrow).

Further evidence for the existence of a fault in this vicinity can be found in the form of a series of isolated outcrops of crushed rock, one of which is exposed in a cutting along the West Coast Highway, below Porter's Pass summit at the point where the old highway rejoins the present. Other outcrops of crushed rock are to be found along that section of the Kowai River bed between the Foggy River Confluence and the Tussock Grasslands Field Station. One such outcrop in the vicinity of the Foggy River Confluence coincides with the point of truncation of Otarama till which lines the right bank of the Kowai River between the field station and this point. The terrace surface carved into this till postdates the Blackwater II Glacial Advance. No displacement of this surface has taken place.

Several large scale slump features along this section of the Kowai River, all of which show several, apparently synchronous phases of movement, are the result of periodic phases of activity along this fault line, having occurred between the glacial advances of Blackwater I and II at approximately 20,000 years B.C. They are probably a consequence of major earthquake. (Fig 4.6.) The development of massive scree slopes along the left bank of the Kowai River between the Foggy River Confluence and the headwaters of Irishman Creek are related to fault activity. Once again several phases of scree development have taken place, evidence for which can be seen in a cross section of an old stable scree deposit on the left bank of Torlesse Stream opposite Helen's Stream.

A crush zone with contrasting lithologies thrust against it, and a well defined scarplet, strikes in a north-easterly direction across the low divide separating the steep, scree-covered slopes of Mount Torlesse from the ice-planed surface of Papanui Road, in the vicinity of the Headwaters of Irishman Creek. This zone coincides with a straight and narrow ridge separating Staircase Gully from the Little Kowai River. A very low saddle between two ice planed divides, separates the Little Kowai River drainage system from the Patterson's Stream drainage system. Just below this saddle, on the Patterson's Stream side, a small exposure of crushed bedrock in association with a red and green chert bed delineates the trend of this fault. No attempt was made to trace this fault beyond Patterson's Stream.

(3) Interesting Features Within Fault Zone

The most noticeable feature is the curious but distinctive drainage pattern exhibited by the Kowai, Rubicon and Little Kowai Rivers. These river courses contain large scale bends across their middle reaches where they flow through low foothill topography. The axis of the bend for each of the three rivers approximately coincide with a straight line drawn between Trig J 1198 m (3929') (Rabbit Hill and

Trig N 824 m (2702'), trending in a SW-NE direction. This trend also coincides approximately with the strike of several large scale fault lines and bedrock foothill ridges, thereby suggesting that many of the features within this area are structurally controlled.

A series of oversteepened outwash terrace levels, approximately one kilometre along the Kowai River from the turnoff leading from the West Coast Highway to the Tussock Grasslands Field Station, can be seen lining the left bank. (Fig 4.7.) This flight of degradational terraces have been carved out of gravel drift, deposited during the Blackwater and Poulter Glacial Advances, upon a bedrock platform. (Profile II.)

It was originally thought that their steepness was due to the damming of the Kowai River by a slump deposit on the right bank and a fan-like feature on the left bank, flanking the upstream end of this set of terraces and thereby providing the steeper than usual gradient. However, it appears that the bedrock platform beneath this series of terraces is also tilted, so that the solution to the problem appears to be of a structural nature and possibly a consequence of dextral block movement along the bounding faults. These terraces lie on the downfaulted side of this fault and dip towards the south and south east. Even the present Kowai gradient reflects the influence of these faults.

The interfluve area between Torlesse and Irishman Streams consists of an irregular, bouldery, steeply inclined surface of uncertain origin. Although partially composed of boulders reworked from nearby till deposits this surface is not morainic. However a small elongate mound along the left side of this valley above the position where Irishman Stream emerges from a bedrock gorge, may be a portion of a small lateral moraine. (Fig 4.8.)

The major surface in question is possibly the result of several recent phases of 'debris flow' type activity resulting in the flushing out of material from the upper reaches of Torlesse Stream during periods of peak flow. The angular nature of the surface boulders shows that the material has not undergone significant fluvial transportation. The bouldery nature of the surface and the paucity of a loess covering indicate that this feature is of a very recent age, probably post glacial. (Profile II.)

II THE KOWAI FAULT

> "West of Springfield a fault-line runs along the base of the Russell Range, the fault-line or fault line scarp being strongly indicated by a series of faceted spurs fronting the Kowai River. (Fig 4.9.) The line of the Kowai Fault runs in close to the small patch of exposed coal measures near the Kowai Bridge, which are crushed and much disturbed stratigraphically, while the hill slopes opposite on the lower spurs of Mount Torlesse are a

Fig 4.7 Series of oversteepened outwash terrace surfaces of Blackwater Age (arrows). The Kowai River is in the foreground and to the right of the photograph.

Fig 4.8 A view of Torlesse Stream Catchment. 'Gingerbread Spur' is indicated by the vertical arrow. The 'debris flow' topography is indicated by the curved arrow. The horizontal arrow is pointing to a suspected moraine remnant. Mount Torlesse is in the background.

Fig 4.9 A view of the Kowai Fault running along the base of the Russell Range. The fault-line scarp is strongly indicated by a series of faceted spurs fronting the Kowai River (arrow). Photograph was taken from lime works looking up the Kowai Valley.

> stripped surface, which continues across the Waimakariri on to the down behind the Woodstock Station, the greensands and underlying beds containing _Conchothyra_ and _Trigonia_, and other shells exposed in the bed of the river near Otarama being a part of the beds which have been faulted down.
>
> An extension of this fault line probably follows, after a slight turn, along the south-eastern flank of the Benmore Range.
>
> The marked break in the topography all along the range, and the similarity in the form of successive ridges as they abut against the sides of Benmore, are to be explained in this way, although there hardly appears to be sufficient evidence on which to base a positive statement of the existence of a fault. Its direction is nearly parallel with what may be regarded as definite fault-lines occurring in other parts of the area. This suggested fault would necessitate a change of throw from the north west to the south east side of the fault, a reversal of displacement amounting to hundreds, if not thousands, of feet. Such a change would be remarkable in a short distance. For these reasons a continuance of the Kowai Fault along the south-eastern flank of the Benmore Range is somewhat doubtful."
>
> (Speight, 1924.)

This work has demonstrated thattectonic activity has been responsible for major disruption and discontinuity in deposits of even the youngest glacial advances. However, there is sufficient ambiguity in the available evidence within this area for quantitative estimates of components of both horizontal and vertical displacement to be uncertain even as to order of magnitude.

CONCLUSIONS

From a plan map and longitudinal profile of glacial terrace levels, drawn up for the entire length of the Kowai River, the various surfaces could be extrapolated and hence traced to their respective moraines.

A distinct terrace surface and moraine system was found for each of the Woodstock, Otarama, Blackwater I and II and Poulter Glacial Advances, from which some idea of the maximum extent of each advance was furnished.

During the Avoca Glaciation, as asserted by Haast (1879, p.392) and more diffidently by Speight (1935, p.309), the Waimakariri and Rakaia Glacier Systems were joined by transfluence through Coleridge Pass and Lake Lyndon Saddle, and coalesced in the piedmont area south-east of the Malvern Hills. Ice planed summits and ridges testify to the existence of Avoca ice within the Kowai, West Branch Kowai, Rubicon and Little Kowai Catchments.

Ice from the Rakaia glacier penetrated the Acheron Valley and invaded the head of the basin of the West Branch Kowai River, across a low divide, in the vicinity of Rabbit Hill during the Woodstock and subsequent Otarama glacial advances.

Glaciers of the Blackwater I, II and Poulter advances originated entirely within the Kowai Catchment, their maximum extent being clearly delineated by well established moraine systems.

Blackwater times were characterised by extensive erosion of outwash gravel deposits along the lower reaches of the Kowai Valley, followed by a phase of aggradation almost to its former level. The timing of this episode is thought to coincide with a series of fault movements, along the "Porter's Pass Fault Zone", that took place between the Blackwater I and II glacial advances at approximately 20,000 years B.P.

Great difficulty was encountered in trying to differentiate deposits and degradational terrace levels of the Poulter Glacial Advance from those of the Post-Glacial period. The overall conclusion drawn from this work is that the stratigraphy and glacial history of the Kowai River Valley reflects that of the Waimakariri Valley very closely.

The New Zealand Geological Map 1:250,000, Sheet 18, Hurunui, 1st Edition; of the N.Z.G.S. Series shows a single major fault trace striking NE-SW from the vicinity of Joyce's Stream, through Porter's Pass and on towards the Rakaia Catchment. Closer investigation has revealed evidence for a fault zone bordered along its western side by the

Porter's Pass Fault and along its eastern margin by a fault trace, here called the 'Benmore Fault', for which abundant evidence is available.

This zone of faulting has tentatively been referred to as "The Porter's Pass Fault Zone".

Several topographical features including numerous large scale slumps, all of which show several apparently synchronous phases of movement; oversteepened outwash terrace surfaces and the distinctive and apparently structurally controlled dog-leg drainage pattern of the Kowai, Rubicon and Little Kowai Rivers, all demonstrate that tectonic activity has been responsible for major disruption and discontinuity in deposits of even the youngest glacial advances.

SECTION TWO - SEDIMENTOLOGY

PART ONE

CHAPTER FIVE

STATISTICAL ANALYSIS OF OUTWASH GRAVELS

I INTRODUCTION

In the previous section, a study of the physiography of the Kowai Valley was made in an attempt to establish the glacial history of the area during the Late Pleistocene.

Four major glacial advances were delineated, from which some indication as to the duration and magnitude of each was determined.

This section is concerned with determining the conditions of transportation and deposition of two outwash gravel horizons belonging respectively to the Woodstock and Otarama Glacial Advances, with the aim of explaining variations in the physical characteristics that exist between them.

Several recessional moraines marking the retreat of the Woodstock glacier have been found. The material comprising the horizon of Woodstock outwash gravel, at the type section, is thought to have been derived from a recessional moraine, here called the 'Benmore Surface'.

The material comprising the horizon of Otarama outwash gravel, at the type section, is thought to have been derived from a suspected terminal moraine of the Otarama glacier in the vicinity of the junction of the Kowai and West Branch Kowai Rivers.

It is suspected that most of the material at the type section has been derived from within the Kowai and tributary valleys and transported to the site of deposition under the combined influence of glacier ice and stream processes over a distance of approximately 14 km. An attempt was made to look for particles of rock types 'foreign' to the Kowai Valley that may have been transported from the Rakaia Valley via the West Branch Kowai River.

II NATURE AND SCOPE OF WORK UNDERTAKEN

In a geological study such as this, there is always a great deal of subjective interpretation based upon scant and often unevenly distributed field evidence. It was therefore undertaken to find a source of objective criteria that could be used to distinguish horizons of outwash gravel that were deposited during a succession of separate glacial episodes.

This section concentrates on the sedimentology of the gravel deposits. It is hoped that through the recording of sediment properties and the use of geomorphic data, the conditions of deposition might be understood. Quite apart from genetic considerations, the author was also interested in any inter-relations among sediment properties.

Because of the nature of the deposits, which in the field show no convincing, surficial characteristic variations; apart from colour, it was felt that the best source of objective criteria would be from a statistical analysis, as it is an empirical rather than a theoretical approach which not only facilitates rapid and easy comparison of large numbers of parameters, but also, renders it simple to point out similarities and differences. Quantitative measures of these parameters is required for precise work.

Unfortunately the geological significance of the measures is not fully known. As of our present state of knowledge, we can make a few educated guesses about the meaning of grain size statistics. In the past it has been generally accepted that the fundamental attributes of sediments, including grain size, sorting, shape and sphericity, are affected to a greater or lesser degree by transportation in streams. Many of the major studies placed great emphasis upon the function of distance of transportation as being the major factor in contributing to changes in grain parameters between source and site of deposition.

While the overall physical characteristics of the Woodstock and Otarama outwash gravel horizons are undoubtedly a function of the distance of transportation, minor but significant variations may be due to other factors including the intensity and duration of each glacial advance. This in turn must produce variations in physical processes such as current strength and hence rate of transportation in the local environment, thereby resulting in possible differences in grain parameters including size, skewness and sorting between deposits transported and deposited during separate glacial episodes.

Probably the most important single factor in determining the overall physical appearance of these deposits is the duration of the time interval during which these processes operated. For example, it is possible that a difference in composition could account for the intense colour variation between the Woodstock and Otarama deposits, however, it is equally attributable to weathering processes. This may indicate that the amount of weathering is in proportion to the age of the Deposit. A detailed compositional account was undertaken to test which of the two hypotheses applied in this instance.

Sphericity and shape were analysed to determine if glacially transported material tends to develop a characteristic or diagnostic shape factor and degree of sphericity. Comparisons of the Woodstock and Otarama samples may reveal variations in these parameters that can be related to differences in intensity, duration and distance of transportation by glacier ice and subsequent modification by water processes. Correlation with other parameters including grain size and composition, within, and between each of the two samples was also attempted.

Undoubtedly some stones have been rounded by earlier water action, but their number and the amount of rounding are believed not to invalidate qualitatively the inferences to be drawn from the comparative percentages.

The degree to which post depositional processes modify grain parameters, if any, is difficult to measure and was not attempted here.

III SAMPLE COLLECTION AND LOCALITY

Several large drums of outwash gravel were collected from various localities along the length of the Kowai River.

It was intended that a sample from each of three outwash gravel units, together with a sample of glavial till would be statistically analysed. Unfortunately, however, the time involved in preparing and analysing just two of the samples was such that analysis of the remainder proved to be impracticable.

The two samples chosen for analysis were collected from the same locality, situated on the right bank of the Kowai River, approximately 5.5 kilometres west of the township of Springfield, on the main West Coast Highway (Map).

The face of the exposure was cleaned to remove any superficial soil and vegetation.

IV THE LITHOLOGIC SUCCESSION AT THE SAMPLE LOCALITY

The lithologic succession consists of three vertically stacked outwash gravel horizons, representing deposition during successive glacial episodes. (Fig. 5.1).

(1) The Woodstock Deposit

(a) Name.

> "The name is taken from Woodstock Station at the lower end of the Staircase Gorge, where the relations of the deposits are most clearly seen." (Gage, 1958.)

(b) Deposits. This lowermost exposed unit consists of a poorly sorted oxidised and deeply weathered, orange-brown, coarse outwash gravel approximately six metres thick. The cobbles are subrounded to rounded and have a distinct weathering ring of variable thicknesses. Sand, silt and clay bind the gravel matrix into a compact deposit. No stratification is visible. A sharp upper horizontal contact is formed with a unit consisting of fine, angular, slope debris of a similar colouration to that of the underlying Woodstock outwash gravel. (Fig. 5.1.)

> "The Woodstock deposits are without doubt the result of vigorous aggradation during a major glacial advance. Deep erosion and weathering of these deposits then prevailed for long enough to reduce Woodstock features to minor remnants and to produce a substantial weathering rind on the constituent pebbles, down to at least 100 metres below the level of the original surface. Objective criteria are lacking but the length of time is thought to have been at least some tens of thousands of years, because visual comparison of the amount of weathering compared with that shown by later deposits suggest a time span much greater than between any two subsequent glacial advances, or between the Otarama advance and the present day." (Gage, 1958.)

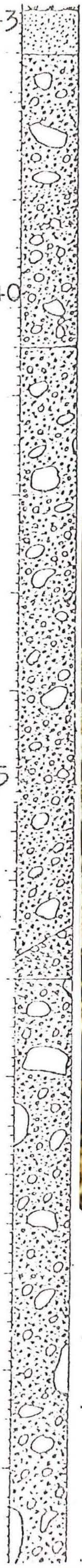
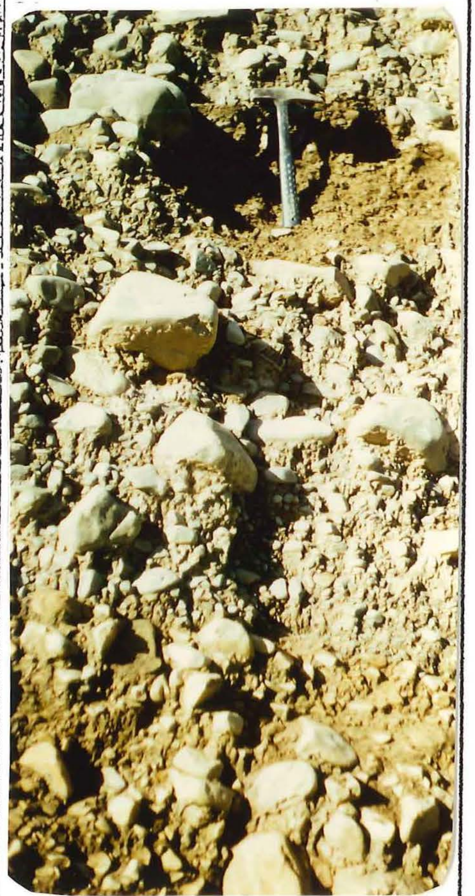
(2) <u>Duration of Woodstock - Otarama Interval</u>

The one distinguishing feature between these two units is their age difference. Moar and Gage's (1973), "re-examination of the Joyce's Stream evidence appears to support the full interglacial status assigned first tentatively and later definitely, by Gage (1958; 1961,) to the Woodstock-Otarama interval, regardless of external correlations."

(3) <u>The Otarama Deposit</u>

(a) <u>Name</u>. The name is taken from "Otarama Station" near Kowai Bush (Map).

(b) <u>Deposit</u>. A sharp upper contact separates the Woodstock Slope deposits from the overlying Otarama

Geological description	Age	Scale in meters above m.s.l.	Graphic log	Photographs
Loess	POST GLACIAL	443		
Poorly sorted, grey, unweathered coarse outwash gravel, loose, friable and cross-bedded.		440		
Sharp contact				
Poorly sorted, dark-brown, coarse outwash gravel. Grey, rounded to sub-rounded cobbles. No stratification. Very compact.unit	OTARAMA	435		
Fine grained, angular slope deposits (not shown in photograph).				
Poorly sorted, deeply weathered, orange brown, coarse outwash gravel. Rounded to sub-rounded cobbles with distinct weathering rind. No stratification Very compact unit	WOODSTOCK	430		

Legend

	Gravel
	Sand
	Silt
	Clay

Figure 5.1 Graphic log of sample locality

outwash gravel unit. The Otarama cobbles are internally comparatively fresher looking than the Woodstock cobbles. Only some of the Otarama cobbles exhibit a weathering rind. This rind is often hazy in outline and of variable intensity and thickness. Overall, this deposit is of a dark-brown colouration and consists of poorly-sorted, subrounded to rounded cobbles bound into a compact unit by sand, silt and clay. This unit is approximately six metres thick and is devoid of sedimentary structures. (Fig. 5.1.)

(4) Cut and Fill Deposit

A sharp contact separates the underlying Otarama deposit from the topmost cut and fill deposit which in turn is capped with fifty or so centimetres of loess. This unit has been deposited upon a bench cut into the underlying Otarama Outwash Gravel. There is no obvious difference in the degree of weathering between these two units, however, there is a slight difference in colouration when the section is viewed from a distance. The deposit consists of coarse, grey-coloured, unweathered, rounded to sub-rounded cobbles and boulders intermixed with a high percentage of pebbles, sand and silt. The texture of the deposit is open and therefore loose and friable. Some evidence of irregular cross-bending is still visible. There is a considerably lesser clay content within this unit than in the previous two underlying deposits. The total thickness of this unit is approximately three metres. (Fig. 5.1).

V SIZE ANALYSES

(1) Review of Previous Work

Since 1900, size analysis has been important in sedimentological studies. Early contributions are largely those of Udden (1898, 1914), and Wentworth (1922, 1929), Trask (1932), Krumbein and Pettijohn (1938), Otto (1939) and others have applied various statistical co-efficients to characterise the size frequency distribution of clastic sediments. Since 1941, there has been considerable advance in measurement techniques by the use of electronic recording systems, especially if the size is determined by the settling velocity method (Zeigler, Whitney and Hayes, 1960).

Formulae for sample statistics have been proposed by Inman (1942), and these have been modified by Folk and Ward (1957). Several papers dealing with interpretation of environments of deposition from the size distribution of clastic sediments include those of Doeglas (1946), Passega (1957), Folk and Ward (1957), Mason and Folk (1958), and Harris (1958).

Important studies in the hydrodynamics viewpoint are the works of Hjulstrom (1939), Inman (1949) and Bagnold (1941, 1956). No general solution as regards the discrimination between the mechanisms and environments of deposition is available. Sahu (1964) attempted such a discrimination using quantitative methods of size analysis.

(2) Laboratory Procedure

Throughout this study the ø (phi) scale, devised by Krumbein (1934) is used in conjunction with Wentworth's (1922), verbal size class terminology. (Fig. 5.2.)

(a) Sieving. Each sample, weighing approximately 300 kg, was wet sieved through a +3ø mesh placed across the top of a forty-four gallon drum. This mesh size was chosen as it was the only one available with a frame of sufficient diameter to fit across the top of these large drums. Each drum was lined with heavy duty plastic to prevent leakage and rust contamination.

The total sample was washed so that the material less than +3ø collected in the drum together with the water. The material larger than +3ø remained upon the sieve mesh. This was air dried and then dry sieved into fractions of 1ø interval.

Phi (ϕ)	Wentworth Size Class	
-12		
-10	Boulder (-8 to -12ϕ)	
- 8	Cobble (-6 to -8ϕ)	
-6		
-4	Pebble (-2 to -6ϕ)	GRAVEL
-2		
-1.75		
-1.5	Granule	
-1.25		
-1.0		
-0.75		
-0.5	Very coarse sand	
-0.25		
0.0		
0.25		
0.5	Coarse sand	
0.75		
1.0		
1.25		
1.5	Medium sand	
1.75		
2.0		SAND
2.25		
2.5	Fine sand	
2.75		
3.0		
3.25		
3.5	Very fine sand	
3.75		
4.0		
4.25		
4.5	Coarse silt	
4.75		
5.0		
6.0	Medium silt	
7.0	Fine silt	
8.0	Very fine silt	MUD
9.0		
10.0	Clay	
11.0		
12.0		
13.0		
14.0		

Figure 5.2 Grain size scales and Wentworth size classes. (From Folk, R.L. 1968)

A total of eighty eight gallons of water was required to wash each sample. By far the greatest problem was to dispose of the water without losing the fine material, of silt and clay size, held in suspension. The drums were left for one month to allow the fines to settle. Measured volumes of water were syphoned off the top, from which a smaller measured sample was centrifuged. The suspended material was dried and weighed to three decimal places using a Mettler balance. The amount was then adjusted for the initial volume of water syphoned off. This process was repeated until all the water had been disposed of.

The residue left in the drums was air dried and sieved into fractions of 1ø interval. All dry sieving was done on the Rotap for periods of twenty minutes per sieve. The material in each phi fraction was weighed and then bagged.

(b) Pipette Analysis. The standard method of pipette analysis outlined in Folk (1968), was utilized.

Calgon was used as a peptizer at a concentration of 0.6 gms per thousand mls.

The total pan fraction for both samples was split many times to obtain a recommended 15 gram sample for use in the pipette analysis.

Withdrawal times differ slightly from those stipulated in Folk (1968). The first five withdrawal times were taken at a depth of 20 cm after intervals of 20 seconds, 2m, 4m, 8m and 15 minutes. Two subsequent withdrawals, to save time, were taken at a depth of 10 cm after 30 minutes and two hours, respectively. This procedure sampled the silt and clay content between $+4\phi$ and $+8\phi$. To obtain further grain size parameters the cumulative curve is extended in a straight line on ordinary arithmetic (squared) graph paper from the last point to $+14\phi$ at 100%. This assumed that essentially all clay particles are larger than $+14\phi$ (0.07 microns).

(c) Results of Sieve Analysis. The sediment in both samples ranges from clay-sized particles to boulder sized material. For ease of handling any material less than $+4\phi$ (mud) was grouped together in the pan fraction. Similarly, material with a diameter greater than -6ϕ (cobbles and boulders) was grouped in the -7ϕ fraction. The total Otarama sample weighed 326 kilograms 391 grams while the total Woodstock sample weighed 300 kilograms 835 grams. (Table 1.) The weight of each fraction expressed as a percentage of the total weight is shown in figures 3(a) and 3(b). The Woodstock sample contains a greater percentage, by weight, of the very coarse cobble and boulder sized material, that is, the -7ϕ fraction, than the Otarama sample.

			WOODSTOCK								OTARAMA							
φ	Lithotypes	Wentworth size classes	Weight	Cum. Wt	%	Cum. %	Weight	%	Cum. Wt	Cum. %	Weight	Cum. Wt	%	Cum. %	Weight	%	Cum. Wt	Cum. %
-7		Cobbles & Boulders	42kg 077gm	42.007	13.99	13.99					34kg 292gm	34.292	10.51	10.51				
-6			22.943	65.020	7.63	21.61					41.697	75.989	12.78	23.28				
-5			20.768	85.788	6.90	28.52					28.334	104.323	8.68	31.96				
-4	GRAVEL	Pebble	33.509	119.297	11.14	39.66	225.780	75.05	225.780	75.05	46.292	150.615	14.18	46.15	269.499	82.58	269.499	82.58
-3			32.015	151.312	10.64	50.30					44.842	195.457	13.74	59.88				
-2			43.063	194.375	14.31	64.61					43.138	238.595	13.22	73.10				
-1		Granule	31.405	225.780	10.44	75.05					30.904	269.499	9.47	82.57				
0		V.C. Sand	19.131	244.911	6.36	81.41					17.305	286.804	5.30	87.87				
+1		C. Sand	14.109	259.020	4.69	86.10					10.403	297.209	3.19	91.06				
+2	SAND	Med. Sand	10.443	269.463	3.47	89.57	67.565	22.45	293.345	97.51	6.620	303.829	2.03	93.09	51.843	15.88	321.342	98.45
+3		Fine Sand	13.339	282.802	4.43	94.00					8.265	312.094	2.53	95.62				
+4		V.F. Sand	10.543	293.345	3.50	97.51					9.248	321.342	2.83	98.45				
PAN	MUD	Silt & Clay	7.490	300.835	2.49	100.00	7.490	2.49	300.835	100.00	5.049	326.391	1.55	100.00	5.049	1.55	326.391	100.00
TOTAL			300.835		100.00						326.391		100.00					

TABLE 1: Weight distribution of material in outwash gravel.

The actual number of boulders and cobbles in both samples, is very small, there being twenty six in the Woodstock sample, weighing 42 kilograms 077 grams, and seventeen in the Otarama sample weighing 34 kilograms 292 grams. These weights make up a significant 14 per cent and 10.5 per cent of the total Woodstock and Otarama samples respectively. (Table 1.)

The date from table one expressed as a cumulative per cent curve (Fig. 5.3c), shows that overall, it is the Otarama and not the Woodstock sample that contains a greater percentage of the coarser grades of material, particularly when the pebble size range between -2ϕ and -5ϕ is taken into consideration. In all the phi grades finer than -2ϕ (granule, sand and mud), the weight percentage is greater for the Woodstock than the Otarama sample. The paucity of sand and mud sized material in the Otarama sample is readily apparent on comparing the weights of each phi size grade with the mean weight of the total sample. The mean weight of the Otarama sample is 25 kilograms 107 grams. From table one it can be seen that the weights of all the phi fractions within the gravel size range of material exceed the mean weight, while the weights of the phi grades within the sand and mud size range are considerably below the mean weight. The same trend is apparent, though less enhanced in the Woodstock sample. The mean weight of the Woodstock sample is 23 kilograms 141 grams.

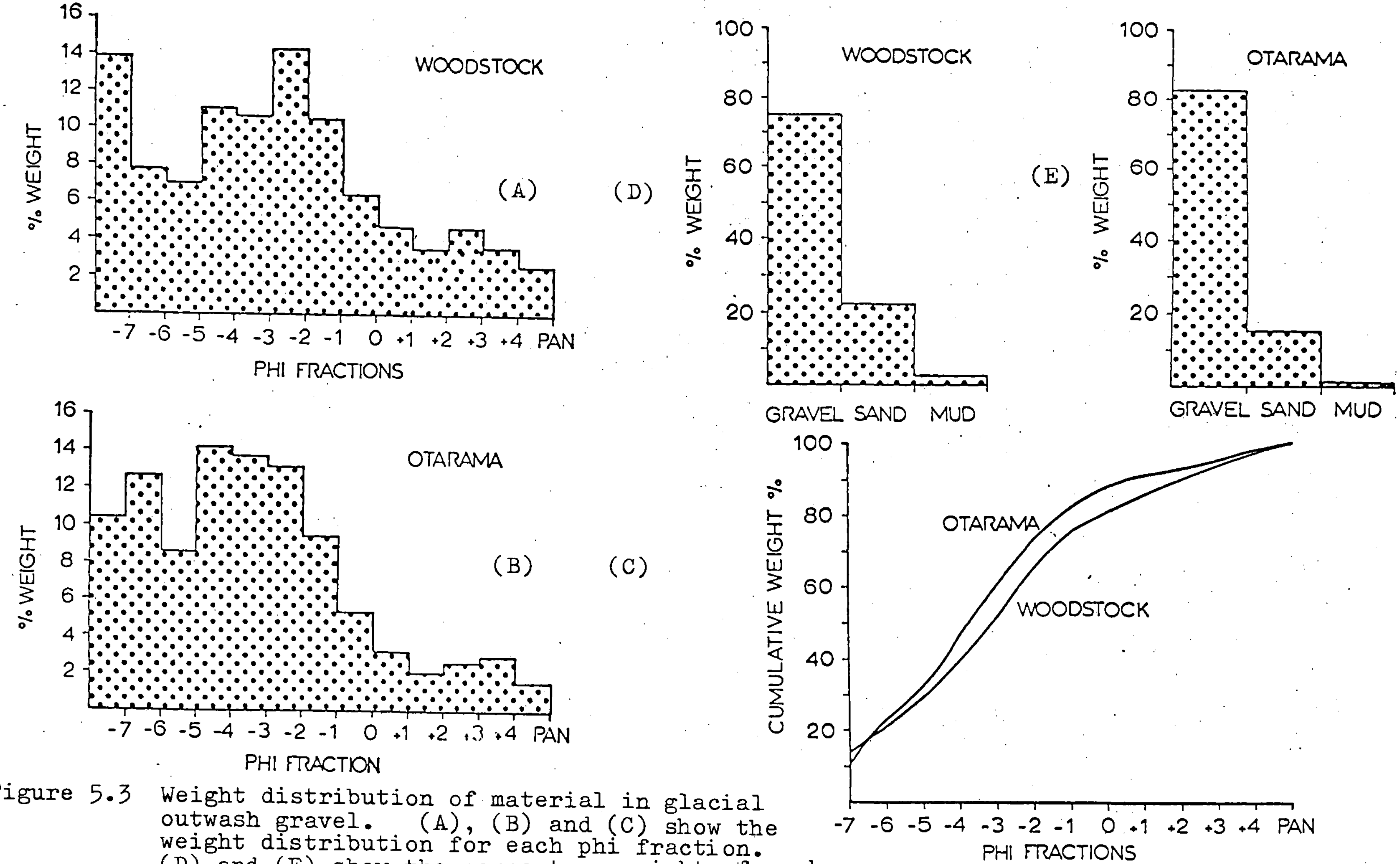


Figure 5.3 Weight distribution of material in glacial outwash gravel. (A), (B) and (C) show the weight distribution for each phi fraction. (D) and (E) show the percentage weight of each lithotype.

The primary weight mode for the Woodstock sample lies within the -2ø fraction while that for the Otarama sample lies within the -5ø size grade, that is, the pebble category (Fig. 5.2.) Secondary weight modes for the Woodstock sample fall within the -7ø (cobble and boulder) size class and -4ø (pebble) size class, while those for the Otarama sample lie within the -3ø (pebble) and -6ø (pebble) size classes. (Fig. 5.3a and 3b).

According to Schlee (1957), a polymodal distribution of grain sizes is thought to suggest and be characteristic of a fluvial environment.

The median weight for the Woodstock sample falls at -3.0ø while that for the Otarama sample lies at -3.6ø, thereby suggesting that overall, the total Otarama sample is approximately half a phi unit coarser than the total Woodstock sample.

In the field, lateral and vertical changes in grain size are both common and abrupt, thereby making an accurate estimate of relative size abundance very difficult. However, some rationalisation is achieved by grouping size classes into general lithotypes: gravel, sand and mud (fig. 5.3d and 3e). Gravel is the most abundant lithotype in both samples. The Otarama sample contains 82.57% by weight of the total sample and the Woodstock sample contains 75.07% (Table 1). Sand is the second most abundant lithotype, by weight in both samples. There is, however, a greater overall percentage of sand in the Woodstock sample, 22.45%, compared with 15.88% in the Otarama sample. Similarly mud forms a greater percentage by weight of the Woodstock sample (2.49%) than of the Otarama sample (1.55%).

(d) Results of Pipette Analysis. The first sample, taken after a twenty second interval from the time that stirring ceased, contained a high percentage of material coarser than +4.0ø, that is, very fine sand sized. The percentage of very fine sand sized material in the Otarama sample was as high as 61.98% while that for the Woodstock sample was 52.91%. (Table 2.) A reversal of the above trend occurs within the coarse silt size range between +4.0ø and +5.0ø. The Otarama sample contains a considerably lesser percentage of coarse silt than the Woodstock sample thus 70.45% of the Otarama sample is coarser than +5.0ø while a large 84.30% of the Woodstock sample is coarser than +5.0ø. This latter trend continues throughout the medium silt (+6.0ø), fine silt (+7.0ø) and very fine silt (+8.0ø) size range. The sample withdrawn after two hours showed that the Otarama sample contains 5.58% clay sized material while the Woodstock sample contains 4.23% clay sized material. From the extrapolated cumulative curve (Fig. 5.4), it can be seen that the difference

WOODSTOCK Sample

Peptizer CALGON Amount peptizer for for 1000 ml. 0.6 gms Mud 15.0 gms

Diameter ϕ	Temp. °C	Withdrawal depth (cm)	Time	Beaker No.	Weight sample + beaker in gms.	Weight beaker in gas	Weight sample in gms less dispersant	X50	Weight Fraction	Cumul. weight	Cumul. per cent
+ 4.0	16	20	20 s.	1	8.003	7.724	0.279	13.350	1.65	1.65	52.91
+ 4.5	16	20	2 m.	2	7.338	7.208	0.130	5.900	7.45	9.10	79.19
+ 5.0	16	20	4 m.	3	7.132	7.031	0.101	4.450	1.45	10.55	84.30
+ 5.5	16	20	8 m.	4	7.780	7.703	0.077	3.250	1.20	11.75	88.54
+ 6.0	16	20	15 m.	5	7.049	6.994	0.055	2.150	1.10	12.85	92.42
+ 7.0	15	10	30 m.	6	7.331	7.288	0.043	1.550	0.60	13.45	94.53
+ 8.0	15	10	2 hr	7	5.277	5.241	0.036	1.200	0.35	13.80	95.77

OTARAMA Sample

Peptizer CALGON Amount peptizer for for 1000 ml. 0.6 gms Mud 15.0 gms

Diameter ϕ	Temp. °C	Withdrawal depth (cm)	Time	Beaker No.	Weight sample + beaker in gms.	Weight beaker in gms	Weight sample in gms less dispersant	X50	Weight Fraction	Cumul. weight	Cumul. per cent
+ 4.0	16	20	20 s.	1	8.622	8.426	.0.196	9.200	5.80	5.80	61.98
+ 4.5	16	20	2 m.	2	8.332	8.154	0.178	8.300	0.90	6.70	65.70
+ 5.0	16	20	4 m.	3	8.196	8.042	0.155	7.150	1.15	7.85	70.45
+ 5.5	16	20	8 m.	4	8.285	8.170	0.115	5.150	2.00	9.85	78.72
+ 6.0	16	20	15 m.	5	8.133	8.052	0.081	3.450	1.70	11.55	85.74
+ 7.0	15	10	30 m.	6	7.115	7.064	0.051	1.950	1.50	13.05	91.94
+ 8.0	15	10	2 hr	7	7.041	7.001	0.039	1.350	0.60	13.65	94.42

TABLE 2: Data sheet for pipette analysis.

in the percentage of clay sized material coarser than +10.0ø, between the two samples is approximately 1.0% and at 12.0ø the difference is about 0.5% in favour of the Otarama sample.

(e) <u>Conclusions for Sieve and Pipette Analysis</u>. The Woodstock sample contains a higher percentage of the cobble and boulder sized material, a lesser percentage of pebble sized material and a greater percentage of material in the granule, sand and mud range of phi sizes, than does the Otarama sample.

Comparisons of the mean weight, primary weight mode and median weights for the two samples tend to indicate that overall, the Otarama sample is slightly coarser than the Woodstock sample.

The pipette analysis indicates that there is a greater percentage, of the 15 grams analysed, of material of the very fine sand grade in the Otarama sample than in the Woodstock sample, and a lesser percentage within the +4ø to +4.5ø, that is, coarse silt grade. For all the grades, between +4.5ø and +8.0ø (medium, fine and very fine silt), there is a greater percentage of material within each grade of the Otarama sample than for the equivalent size grades of the Woodstock sample.

Similarly, in each of the size grades between +8.0ø and +14.0ø, there is a greater percentage of clay sized material for the Otarama sample than for the equivalent grades of the Woodstock sample.

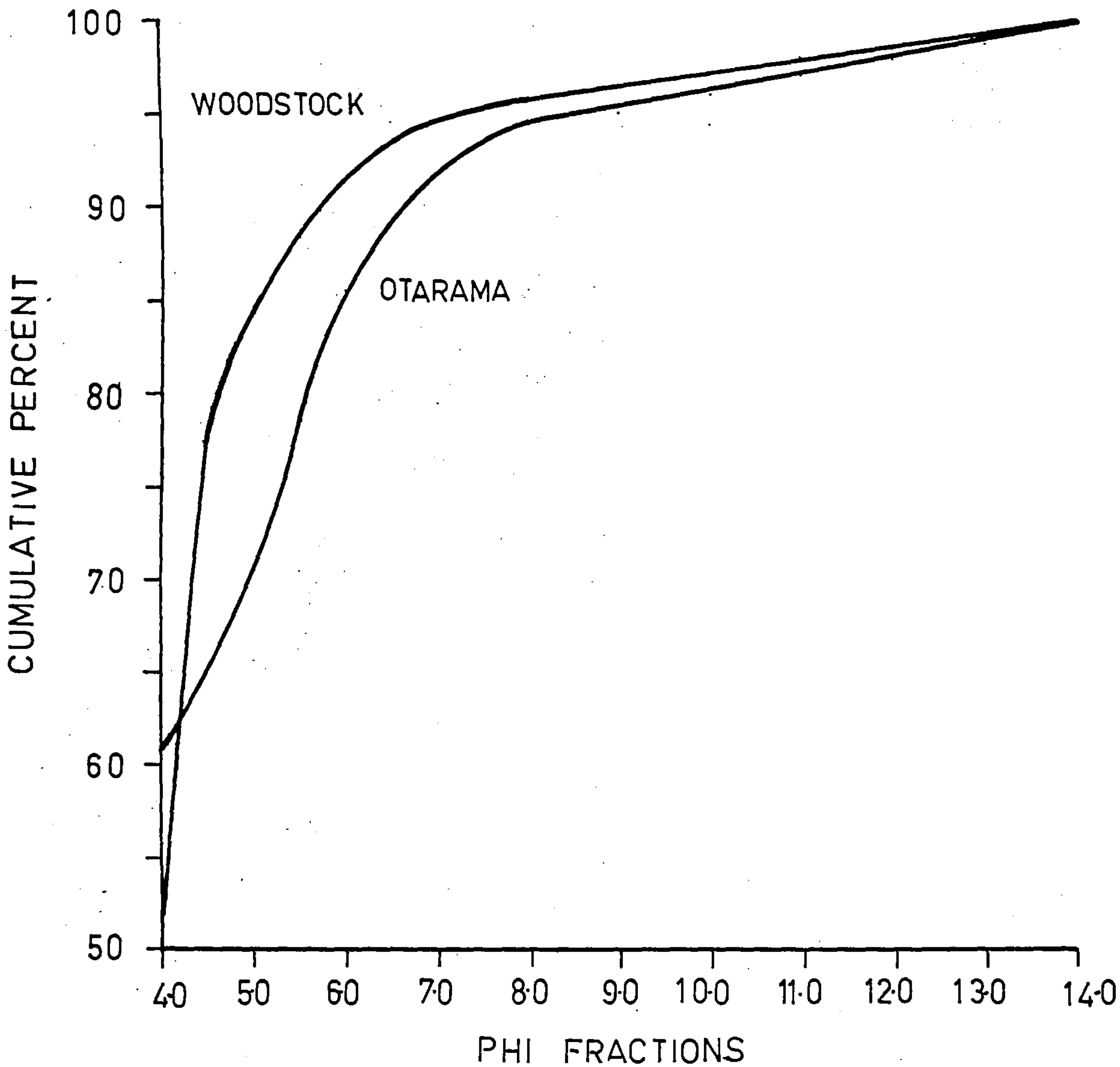


Figure 5.4 Cumulative curve of pipette analysis results.

The differences in the relative abundances of the various grain size fractions can be explained either in terms of (1) slight variations in the local hydraulic conditions that existed during the time of deposition of these two outwash gravel units, or of (2) sorting action of the two transporting mechanisms that operated during the glacial advances, or (3) in terms of a deficiency of particular sized material in the source area.

The sand, silt and clay material act in part as a binding agent through adhesion and compaction in the finer grades, aided by infiltration and precipitation of iron oxides.

The effects of these processes are more apparent within the Woodstock gravels than for the Otarama deposits. The degree of compaction, paucity of sedimentary structures, lack of open work gravel beds and porocity-packing considerations suggest that the gravel and sand fractions were deposited contemporaneously, to give a uniform textural appearance to the deposits.

VI SIZE DISTRIBUTION PARAMETERS

(1) Definitions and Formulae

The parameters used in this paper are those which have been defined by Folk (1968). These are based on percentile measurements in phi scale. Regardless of how the parameters are defined, five different ones are generally used. These parameters and their formulae are as follows:

(a) Median Diameter: that size such that 50 per cent of the particles are larger and 50 per cent smaller. It is generally preferred to the mean diameters as a measure of central tendency as it is less influenced by skewness and; therefore, serves as a better approximation of the modal diameter.

$$Md = \phi\,50$$ (This is the 50th percentile).

(b) Mean Diameter: the average size. It is the function of

(i) the size range of available materials and (ii) amount of energy imported to the sediment, which depends on the transporting mechanism. (Folk, 1968.)

$$Mz = \frac{\phi\,16 + \phi\,50 + \phi\,84}{3}$$

(c) Sorting or Dispersion: a measure of the spread of the distribution. It would correspond, more or less, with the standard deviation of standard statistical methods. Sorting is a measure that is poorly understood. It depends on at least four major factors:

(i) - size range of the material supplied,

(ii) - type of deposition,

(iii) - current characteristics,

(iv) - time-rate of supply of detritus compared with efficiency of the sorting agents. (Folk, 1968.)

Folk's term is Inclusive Graphic Standard Deviation

$$6_1 = \frac{\phi\,84 - \phi\,16}{4} + \frac{\phi\,95 - \phi\,5}{6.6}$$

Perfect sorting would give a value of zero with all other conditions giving higher results.

(d) Skewness: a measure of symmetry of the distribution curve. In a normal distribution the mean and median coincide and the distribution curve is symmetrical, but if they depart from each other, the distribution is skewed. If the mean is greater (in ϕ units) than the median, the curve has a positive skewness; if less, a negative skewness. In a normal distribution the skewness value equals zero. Folk's term is Inclusive Graphic Skewness.

$$Sk_1 = \frac{\phi\,84 + \phi\,16 - 2\,\phi\,50}{2\,(\phi 84 - \phi 16)} + \frac{\phi\,95 + \phi\,5 - 2\,\phi\,50}{2\,(\phi 95 - \phi 5)}$$

The limits of this measure are from +1.00 to -1.00.

(e) Kurtosis: a measure of the peakedness of the curve. In a normal distribution kG = 1.00. Curves that are leptokurtic have values over 1.00 while those that are platykurtic have values less than 1.00. Theoretically the lower limit to this measure is 0.41 with no upper limit but Folk has indicated that most sediments have a kG range between 0.60 and 5.00. Folk's term is graphic kurtosis

$$KG = \frac{\phi 95 - \phi 5}{2.44\,(\phi 75 - \phi 25)}$$

Of the different methods of size analysis, graphic methods of obtaining sample statistics are easier and less time consuming than the moments method.

(2) Results

(a) Mean, Median and Sorting vs Composition. The mean grain size of the total Woodstock sample is -3.0ø for the median diameter and -3.0ø for the mean diameter, with a range of -3.1ø (Coarse grained sandstone) to +3.1ø (Quartz) for the median diameter, and a range of -2.63ø (coarse grained sandstone, to +2.83ø (Quartz) for the mean diameter. (Table 4.) The sorting values range from 3.86 (coarse grained sandstone) to 2.60 (Quartz). (Table 4.) The mean sorting value for the total Woodstock sample is 3.38, that is very poorly sorted. (Table 3.)

The mean grain size of the total Otarama sample is -3.6ø for the median diameter and -3.6ø for the mean diameter, with a range of -3.6ø (coarse grained sandstone) to +3.2ø (Quartz) for the median diameter, and a range of -2.97ø (coarse grained sandstone), to +3.00ø (Quartz) for the mean diameter. (Table 4.) The sorting values range from 3.81 (coarse grained sandstone) to 1.69 (Quartz). The mean sorting value for the whole sample is 3.03, that is, very poorly sorted. (Table 3.)

(b) Skewness vs Composition. Skewness values for the Woodstock sample range from +0.12 (fine skewed, coarse grained sandstone) to -0.42 (strongly coarse

	Mean	Wentworth Size Class	Median	Sorting	Verbal Sorting	Skewness	Verbal Skewness	Kurtosis	Verbal Kurtosis
WOODSTOCK	-3.0ø	Pebble	-3.0ø	3.38	Very poorly sorted	+0.096	Near symmetrical	0.928	Platykurtic/ Mesokurtic
OTARAMA	-3.6ø	Pebble	-3.6ø	3.03	Very poorly sorted	+0.163	Fine skewed	1.034	Platykurtic/ Mesokurtic

TABLE 3: Summary of textural parameters.

	WOODSTOCK					OTARAMA				
Composition	Median	Mean	Wentworth Size Class	Sorting	Verbal Sorting	Median	Mean	Wentworth Size Class	Sorting	Verbal Sorting
CSS	-3.1	-2.63	Pebble	3.86	Very poorly sorted	-3.6	-2.97	Pebble	3.81	Very poorly sorted
FSS	-0.4	-0.23	Very coarse sand	3.59	Very poorly sorted	-0.2	+0.03	Very coarse sand	3.05	Very poorly sorted
Chert	+0.2	-1.07	Granule	3.85	Very poorly sorted	+0.9	+0.70	Coarse sand	2.98	Very poorly sorted
Argillite	-0.1	-0.20	Very coarse sand	2.71	Very poorly sorted	-0.1	-0.10	Very coarse sand	3.28	Very poorly sorted
Volcanics	+0.7	0.000	Very coarse /coarse sand	3.07	Very poorly sorted	-2.3	-1.33	Granule	2.80	Very poorly sorted
Quartz	+3.1	+2.83	Fine sand	2.66	Very poorly sorted	+3.2	+3.00	Fine sand/ very fine sand	1.69	Poorly sorted

TABLE 4: Size distribution parameters.

skewed chert). (Table 6.) The mean skewness value of the total sample is +0.096, that is, near symmetrical (Table 6).

Skewness values for the Otarama sample range from +0.47 (strongly fine skewed, volcanics) to -0.07 (near symmetrical, chert). (Table 6.) The mean skewness value for the total Otarama sample is +0.163, that is, fine skewed.

The skewness calculated from polymodal distributions is not representative of the skewness of any one of the modes exhibited in the unit but is rather a measure of the relative importance of the individual modes. Since the mode in the large size range is the primary one for both the Woodstock and Otarama samples, the phi skewness is positive.

(c) Kurtosis vs Composition. The kurtosis value range is low for both samples. The range of kurtosis values for the Woodstock sample is from 0.67 (platykurtic, volcanics) to 1.79 (very leptokurtic, quartz). (Table 5.) The mean kurtosis value is 0.928, that is, platykurtic to mesokurtic. For the Otarama sample the kurtosis value range is from 0.72 (platykurtic, chert) to 1.10 (mesokurtic, quartz). (Table 5.) The mean kurtosis value is 1.034, that is platykurtic to mesokurtic.

	WOODSTOCK		OTARAMA	
Composition	Kurtosis	Verbal Kurtosis	Kurtosis	Verbal Kurtosis
Coarse sandstone	0.79	Platykurtic	0.79	Platykurtic
Fine sandstone	0.90	Platykurtic	0.89	Platykurtic
Chert	0.96	Mesokurtic	0.72	Platykurtic
Argillite	1.30	Leptokurtic	0.81	Platykurtic
Volcanics	0.67	Platykurtic	0.78	Platykurtic
Quartz	1.79	Very leptokurtic	1.10	Mesokurtic

TABLE 5: Kurtosis values for each composition.

	WOODSTOCK		OTARAMA	
Composition	Skewness	Verbal Skewness	Skewness	Verbal Skewness
Coarse sandstone	+0.12	Fine skewed	+0.26	Strongly fine skewed
Fine sandstone	+0.0	Near symmetrical	+0.10	Near symmetrical
Chert	-0.41	Strongly coarse skewed	-0.07	Near symmetrical
Argillite	-0.12	Coarse skewed	-0.06	Near symmetrical
Volcanics	-0.33	Strongly coarse skewed	+0.47	Strongly coarse skewed
Quartz	-0.13	Coarse skewed	-0.10	Near symmetrical

TABLE 6: Skewness values for each composition.

(3) Conclusions

Attempts were not made to look for relationships between kurtosis and sorting as a function of mean size, as previous writers have found that no relationship exists between kurtosis and grain size nor between sorting and grain size. Several writers have reported that an apparent decrease in mean size is followed by a corresponding decrease in skewness. This was observed in this study.

The Otarama sample is more positively skewed towards the larger sizes and has a larger mean grain size than the overall Woodstock deposit.

If the 'original' skewness and mean values at the source can be assumed to have been similar for both the Woodstock and Otarama samples, the apparent difference in these values at the sample locality can be explained in terms of the combined effect of abrasion and selective transportation. If so then probably more important than wear is the effect of selective transport. In stream transport the smaller particles outrun the larger ones which works to normalise the size distribution, thereby reducing the skewness. Although the number of samples is limited, it is apparent that skewness is a function of the mean size so that the sample with the largest mean particle size (Otarama) also has the most positively skewed distribution.

The relationship between composition and grain size is apparent, whereby the extreme values of median, mean and sorting invariably correspond with the compositions, coarse grained sandstone and quartz, as it is these compositions that dominate their respective pebble and fine sand size classes. This relationship is dealt with further in the following section.

A summary of the statistical parameters is given in Table 3. From this table, the mean and median diameters within each of the two samples are seen to be the same. This together with the information in tables 5 and 6, indicating that the skewness values of the various compositions, in most cases, approximate 0.0 while the kurtosis values approximate 1.00, tends to suggest that in each of the samples the distribution is essentially normal.

Because the material examined was taken from deposits somewhat closely associated with till, and in a situation indicating that the waters in which they were laid down drained glaciers, we expected to find such deposits imperfectly sorted. (Table 3.)

There is no relationship between sorting and composition, skewness and composition or between kurtosis and composition.

VII COMPOSITION

The variety of rock types present include coarse grained sandstone (CSS), fine grained sandstone (FSS), red and green chert (CH), black argillite (ARG), volcanics (VOL), quartz (QZ) and breccia (BR).

The term 'volcanics' is used here in a loose sense to incorporate coarse grained dolerite and fine grained basic basalt.

(1) Method of Analysis

For the fractions including, and greater than -3ø, compositional counts took into account the total number of particles present within each of the two samples analysed. These grades were hand sorted.

For the remainder of the fractions between -2ø and the pan fraction, compositional counts were attempted from a subsample obtained from the multiple splitting of the total amount of material in each phi unit. A binocular microscope was used in conjunction with a point counter to record approximately two thousand five hundred grains from each phi fraction, randomly counted by removing them individually with a seeker from the periphery of the microscope sample. The information collected was converted into percentages and presented in tables 7 and 8, and figures 5.5 to 5.17. Figures 5.5 to 5.17 show:

(a) Percentage of each individual compositional type, e.g. coarse grained sandstone vs phi sizes ranging from -7ϕ to the pan fraction. (Figures 5.5-10.)

(b) Cumulative percent of each individual compositional type versus phi sizes ranging from -7ϕ to the pan fraction. (Figures 5.5-10.)

(c) Percentages of the full range of compositions for each individual phi size ranging from -7ϕ to the pan fraction. (Figures 5.11-17.)

(2) Results

(a) Composition vs Grain Size. Figures 5.5 and 5.10 show the distribution of coarse grained sandstone and quartz, respectively, with regard to grain size. A reciprocal pattern is indicated whereby a decrease in the percentage of the coarse grained sandstone with a corresponding decrease in grain size is matched by an increase in the percentage of quartz grains with decreasing grain size. This trend is apparent in both the Otarama and Woodstock samples.

This concentration of quartz grains in the finer phi fractions is due to the loss of other rocks by abrasion and breakage. This is particularly true for the coarse grained sandstone which although is composed mainly of hard quartz grains, it is the least resistant of all the rock types to abrasion and breakage, probably on account of its high friability. Plumley (1948), made a study of the effect of

	Coarse Sandstone		Fine Sandstone		Volcanics		Chert		Argillite		Quartz		Breccia		Miscellaneous		Total
φ	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%
-7	100	12.42	-	0	-	0	-	0	-	0	-	0	-	0	-	0	100
-6	68.75	20.97	17.86	6.97	-	0	4.46	17.53	1.79	6.33	7.14	5.94	-	-	-	-	100
-5	77.53	30.61	17.42	13.77	2.25	3.45	-	17.53	1.11	10.25	1.69	7.35	-	-	-	-	100
-4	85.83	41.28	6.07	16.14	6.28	13.07	0.48	19.42	0.48	11.95	0.64	7.86	-	-	0.16	-	100
-3	76.99	50.85	13.67	21.47	7.38	24.39	1.25	24.33	0.39	13.33	0.32	8.14	-	-	-	-	100
-2	60.11	58.32	27.76	32.30	6.26	33.98	0.69	27.04	3.63	26.17	1.56	9.44	-	-	-	-	100
-1	67.17	66.66	27.21	42.92	0.56	34.84	1.67	33.61	2.09	33.56	1.30	10.52	-	-	-	-	100
0	54.87	73.48	30.35	54.77	3.68	40.48	3.41	47.01	5.15	51.77	2.86	12.90	-	-	-	-	100
+1	47.98	79.45	25.77	64.82	9.63	55.24	4.20	63.52	6.25	73.87	6.17	18.04	-	-	-	-	100
+2	43.50	84.85	23.66	74.06	10.67	71.60	3.75	78.26	2.50	82.71	15.88	31.25	-	-	-	-	100
+3	42.97	90.19	23.75	83.32	8.05	83.94	2.29	87.26	2.29	90.81	20.63	48.41	-	-	-	-	100
+4	40.35	95.21	22.02	91.92	6.21	93.45	1.71	93.99	1.65	96.64	28.06	71.76	-	-	-	-	100
Pan	38.59	100	20.71	100	4.27	100	1.53	100	0.95	100	33.95	100	-	-	-	-	100
Total	64.28	-	18.47	-	4.70	-	1.83	-	2.04	-	8.66	-	-	-	0.02	-	100

TABLE 7: Percent and cumulative percent for compositions found within the Woodstock outwash gravel sample.

	Coarse Sandstone		Fine Sandstone		Volcanics		Chert		Argillite		Quartz		Breccia		Miscellaneous		Total
φ	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%	Cum. %	%
-7	100	13.54	-	0	-	0	-	0	-	0	-	0	-	0	-	0	100
-6	82.67	24.78	7.18	3.08	-	0	-	0	7.73	5.46	2.22	1.97	-	-	-	-	100
-5	87.20	36.59	5.88	5.60	1.73	4.96	2.42	6.20	1.38	6.44	1.04	2.90	0.35	-	-	-	100
-4	82.64	47.79	4.91	7.70	2.89	13.24	2.20	11.86	6.62	11.11	0.28	3.15	0.23	-	0.23	-	100
-3	48.39	54.34	22.18	17.21	9.07	39.23	1.21	13.81	19.15	24.64	-	3.15	-	-	-	-	100
-2	54.64	61.75	23.60	27.32	5.15	53.98	1.34	18.40	14.47	34.86	0.81	3.87	-	-	-	-	100
-1	54.72	69.16	32.60	41.17	1.13	57.22	3.30	26.87	7.10	39.88	1.62	5.31	-	-	-	-	100
0	40.91	75.92	26.24	52.41	2.65	64.81	4.48	38.36	13.53	49.43	3.19	8.14	-	-	-	-	100
+1	43.44	81.81	22.81	62.19	2.26	71.29	4.95	51.06	20.49	63.91	6.05	13.52	-	-	-	-	100
+2	37.16	86.84	24.04	72.49	4.25	83.47	6.06	66.62	11.86	72.29	16.61	28.29	-	-	-	-	100
+3	33.61	91.40	22.54	82.15	2.80	91.49	4.12	77.19	15.04	82.91	21.87	47.73	-	-	-	-	100
+4	30.71	95.55	21.49	91.36	1.72	96.42	4.88	89.71	12.99	92.09	28.21	72.81	-	-	-	-	100
Pan	32.80	100	20.15	100	1.25	100	4.01	100	11.20	100	30.59	100	-	-	-	-	100
Total	56.78	-	17.95	-	2.68	-	2.98	-	10.90	-	8.65	-	0.04	-	0.02	-	100

TABLE 8: Percent and cumulative percent for compositions found within the Otarama outwash gravel sample.

abrasion and breakage on rock particles during stream transport and compiled a list of rock types in order of increasing resistance: sandstone, volcanics, quartz and chert.

The comparatively high percentage of quartz found in the -6ø size range of the Woodstock sample is somewhat misleading. A few large boulder sized pieces of vein quartz were found and as the total number of particles within this size fraction was small, the quartz accounted for a considerable percentage of the total composition. Apart from this anomaly the histograms in figure ten, showing the distribution of quartz throughout the given phi size range, are remarkably similar. Table 9 shows that the quartz content expressed as a percentage of the total sample is almost identical for both the Woodstock and Otarama samples, being approximately 8.6%. Table 4 shows that the mean grain size of quartz particles, for both the samples, lies within the fine sand size grade.

The distribution of coarse grained sandstone is somewhat more erratic, varying from 100% in the -7ø fraction of both samples to 32.80% and 38.59% in the pan fractions of the Otarama and Woodstock samples respectively. Secondary modes in the distribution of coarse grained sandstone are generally one phi grade coarser for the Otarama than for the Woodstock sample. (Figure 5.5.) The mean grain

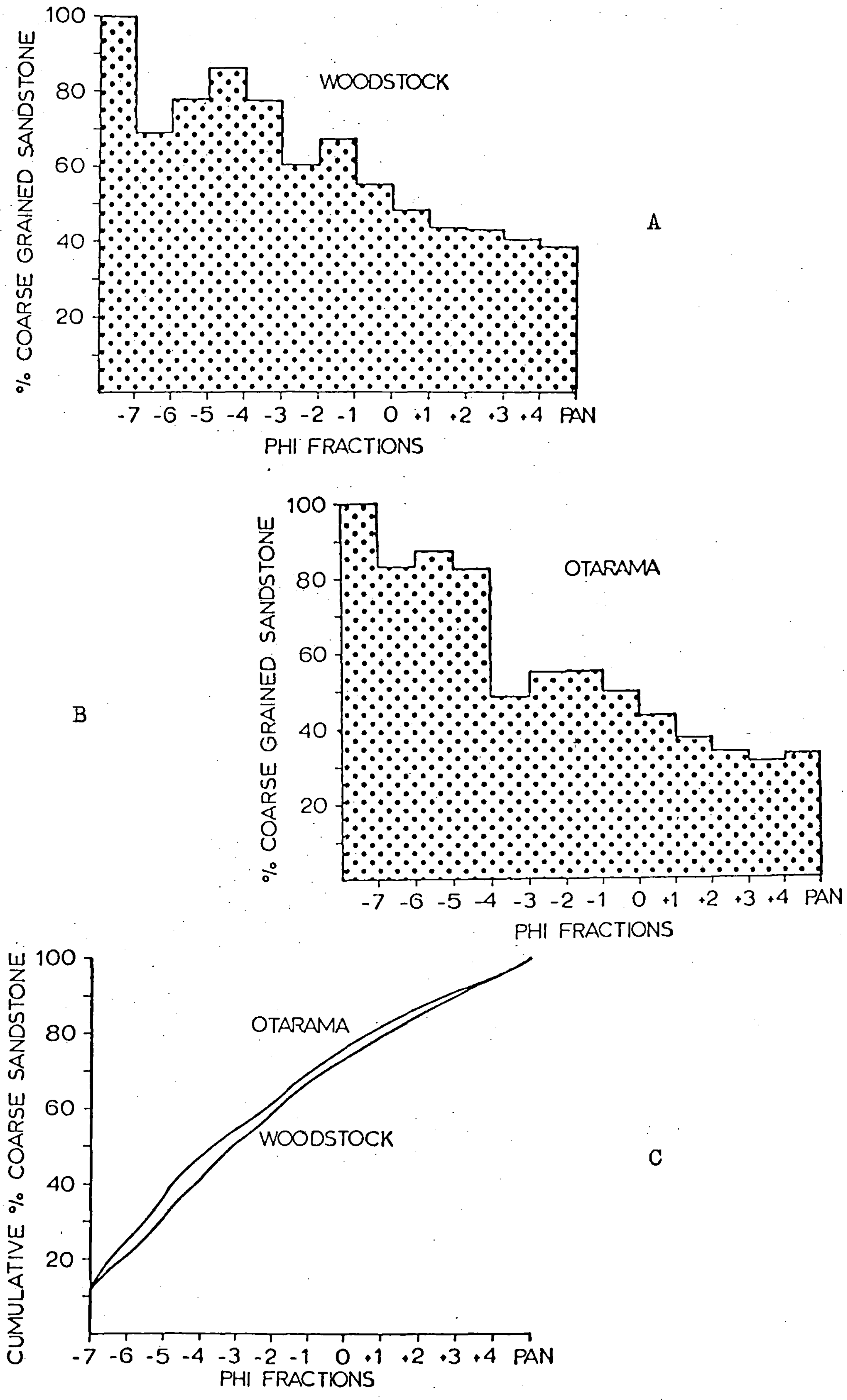


Figure 5.5 Size distribution of coarse grained sandstone particles.

size for both samples falls within the pebble size class. (Table 4.)

The grain size distribution of fine grained sandstone once again shows a similar pattern for both samples, with the greatest variations occurring in the coarser phi sizes between -3ø and -7ø. (Figure 5.6.) The mean size, for both samples, falls within the coarse sand size range. (Table 4.)

There is no similarity in the histograms showing the grain size distribution of argillite for the Woodstock and Otarama samples. (Figure 5.9.) One notable difference is the relative abundance of argillite in each sample. (Figure 5.9.) This is discussed further under the next heading.

The mean grain size for both samples is very similar, being -0.2ø in the Woodstock sample and -0.1ø in the Otarama sample, that is, both fall within the very coarse sand size range. (Table 4.)

The Chert content of the Woodstock sample has a mean diameter of -1.07ø, that is, within the granule size class, whilst the volcanics have a mean diameter of 0.00ø and lie within the very-coarse sand to coarse sand size grade. (Table 4.) This complies favourably with Plumley's (1948) observations regarding relative resistances to abrasion of the various rock types. However, within the Otarama sample there is an apparent reversal of the above trend whereby the volcanics

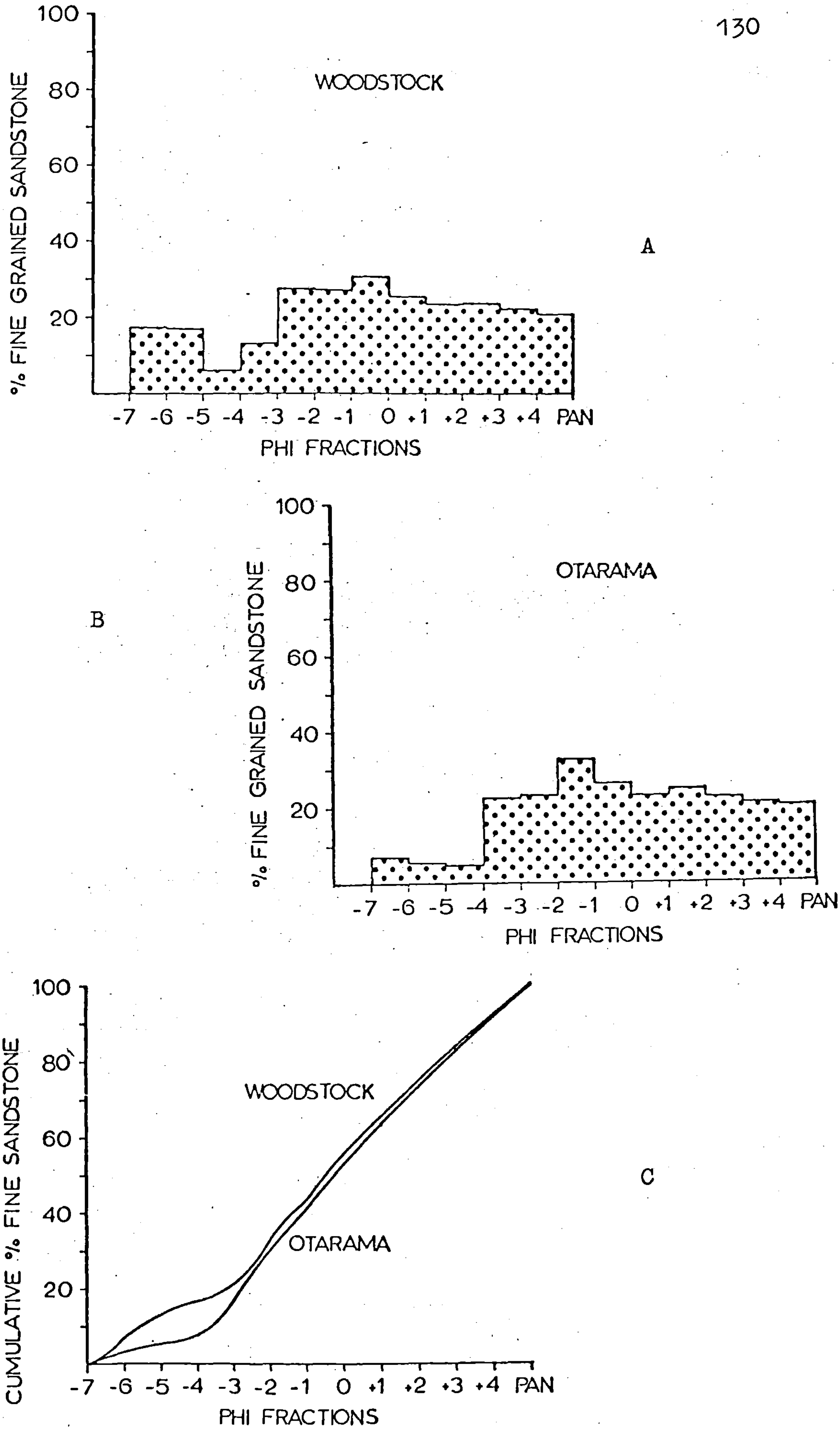


Figure 5.6 Size distribution of fine grained sandstone particles.

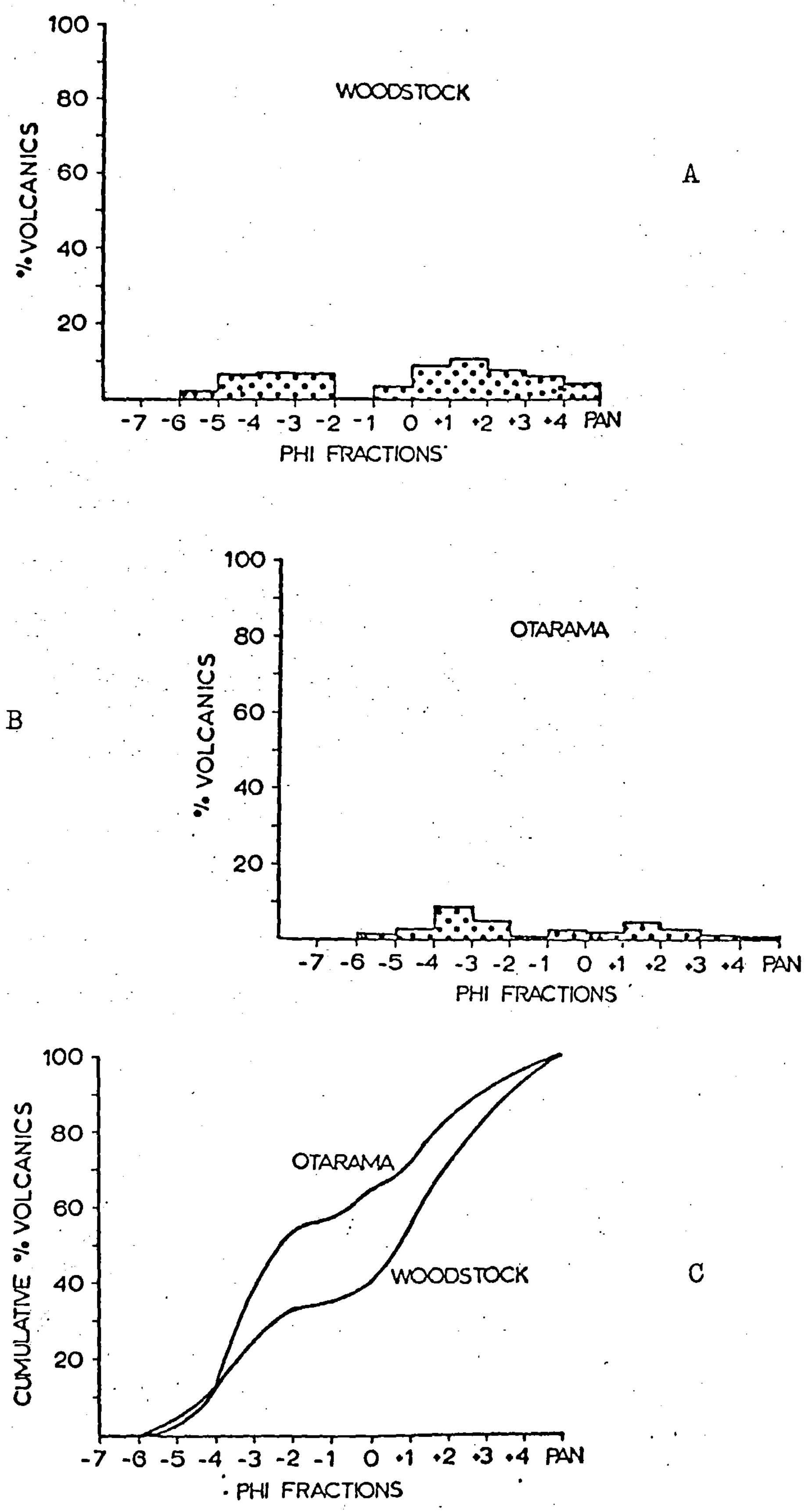


Figure 5.7 Size distribution of volcanic particles.

have a greater mean grain size (-1.33ø), that is, within the granule size grade, than that of the more resistant chert with a mean grain size of (+0.70ø) falling within the coarse sand size grade. (Table 4.) The grain size distribution of the volcanics in both samples is bimodal. (Figure 5.7.)

It is apparent that the solution is related to the source area which furnishes detritus to the streams, and in particular the availability and freshness of the exposures.

The volcanic fraction of the Woodstock sample is predominantly composed of fine grained basalt with a lesser amount of coarse grained dolerite.

The source of the dolerite is from Irishman Creek, a tributary of Torlesse Stream. The source of the basalt is from the dykes found intruding an outlier of Tertiary marine sediments in the upper reaches of the West Branch Kowai River.

The volcanic fraction of the Otarama sample is predominantly composed of coarse grained dolerite together with a lesser amount of basalt.

This difference in the predominance of one volcanic constituent over another explains the bimodal grain size distribution, which in turn is directly related to the glacial advances during Woodstock and Otarama times.

The dolerite particles would have been transported by Woodstock ice down the Kowai River and mixed with basalt particles carried by an ice lobe from the Rakaia Catchment that extended down the West Branch Kowai River past the outlier of Tertiary sediments.

During the succeeding Otarama Glacial Advance ice once again extended down the Kowai River carrying dolerite particles, however, within the West Branch Kowai River the Otarama ice only just managed to top the saddle below Rabbit Hill and did not therefore erode into the Tertiary sediments and associated basalt intrusions. As a consequence the supply of basalt to the Kowai River was greatly reduced so that the Otarama outwash gravel sample not only contained a greater proportion of dolerite than basalt, but also the overall grain size tended to be greater on account of the initial grain size of the predominant parent material.

One possible solution as to why chert has a smaller mean grain size in the Otarama deposit than in the Woodstock deposit may be, that during the Woodstock advance fresh chert beds were exposed by ice and eroded into blocks of varying sizes, which during transportation broke down into the size grades found at the sample locality, over the relatively short distance of 14 kilometres. During the long interglacial that followed much of the exposed chert in the source area would be so badly weathered and so

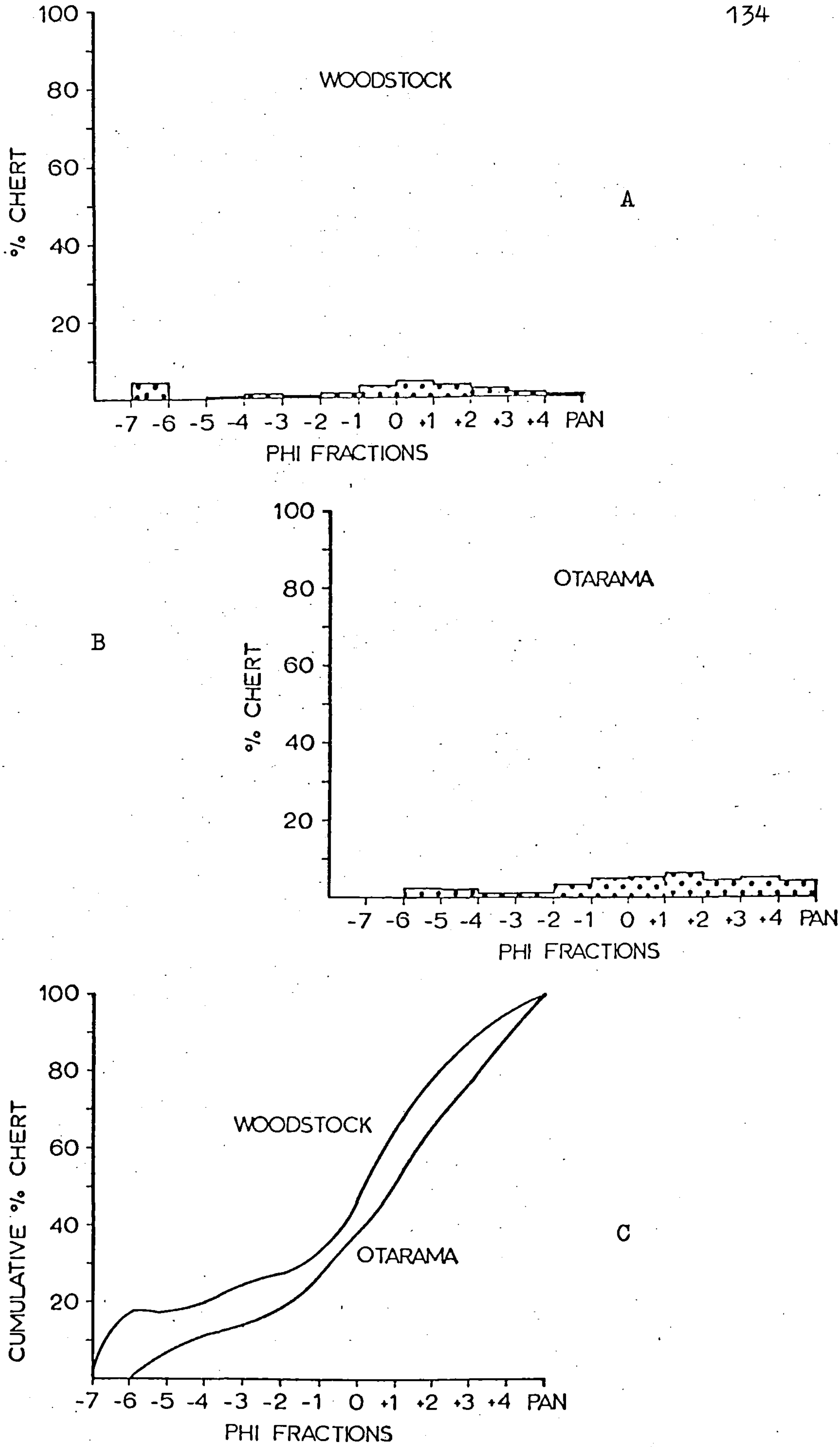


Figure 5.8 Size distribution of chert particles.

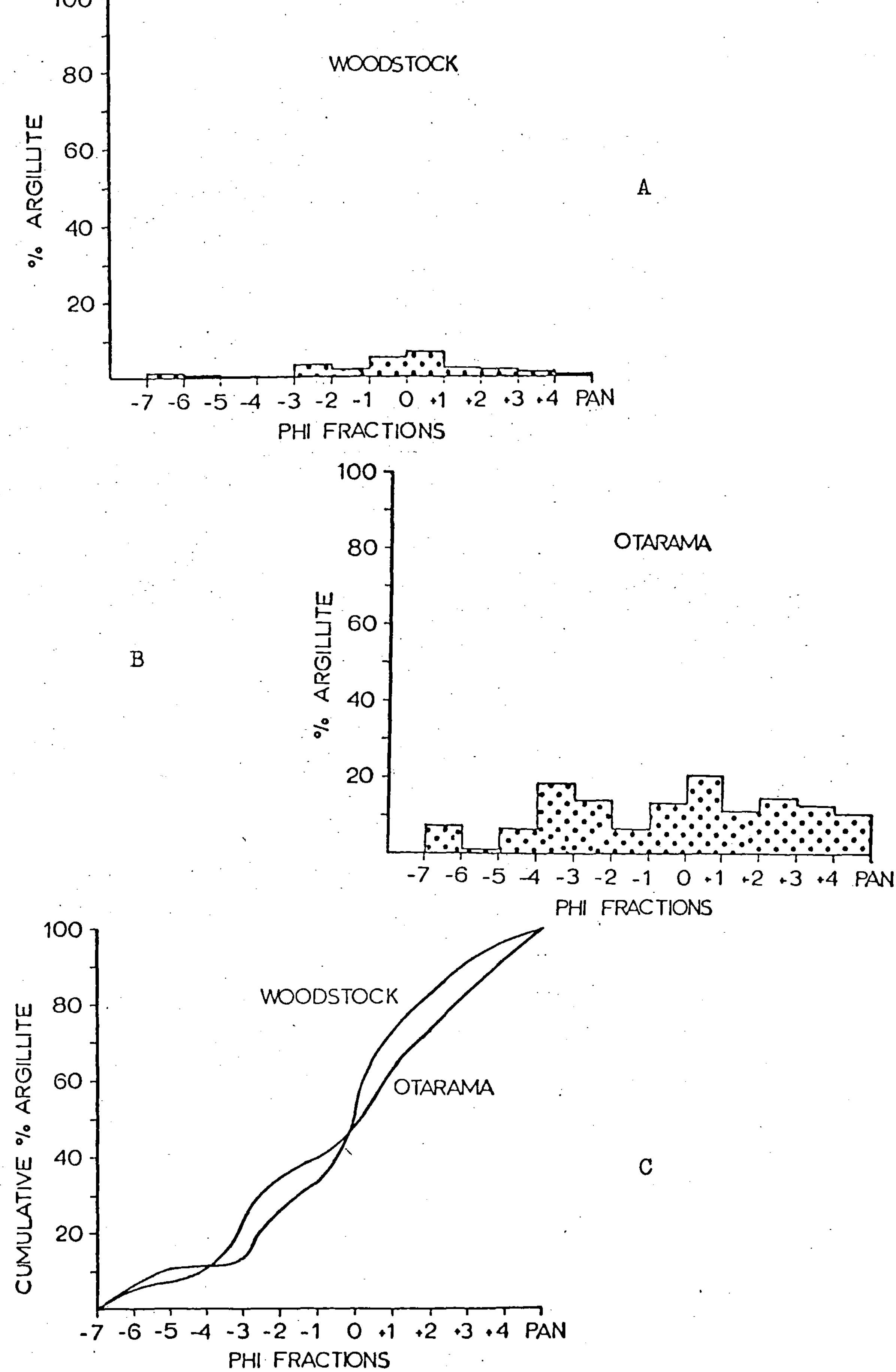


Figure 5.9 Size distribution of argillite particles.

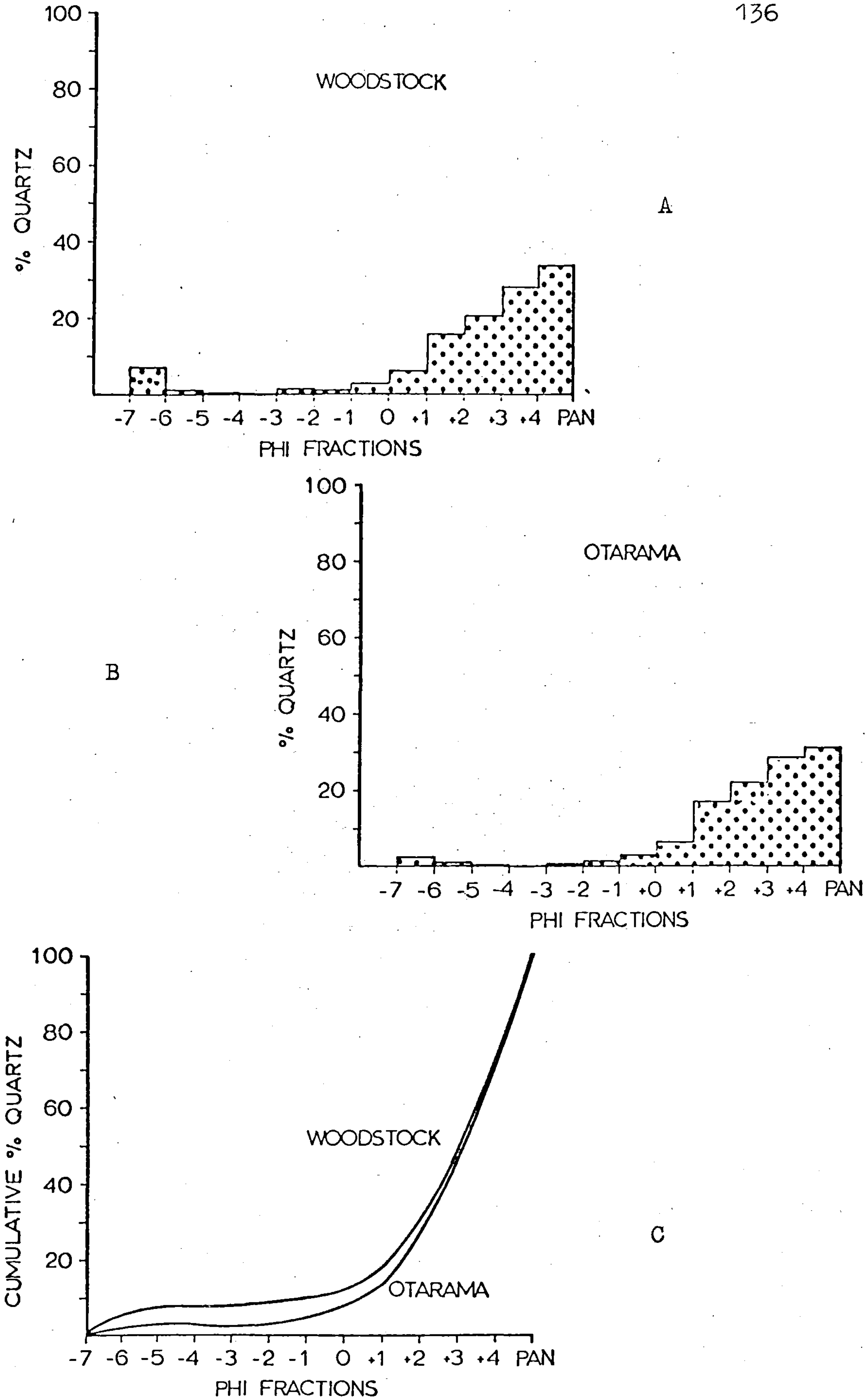


Figure 5.10 Size distribution of quartz particles.

rotted that during its subsequent erosion and transportation during Otarama times, the chert would abrade easily and attain a much smaller mean grain size than the chert within the Woodstock sample, despite the fact that it was transported over an equivalent distance. Outcrops of weathered chert can be found in the headwaters of the Kowai River. In some localities only a clayey chalklike residue remains.

(b) Percentage Composition vs Compositional Range. Figures 5.11 to 5.17 inclusively illustrate the percentages of the full range of compositions within each phi fraction. The largest phi fraction (-7ø) is composed entirely of coarse grained sandstone cobbles and boulders, in both samples. (Figure 5.11.)

The absence of other compositions within this phi size is in part due to sampling error, for volcanic boulders and cobbles were noted in the Otarama deposit at the sample locality. However, nowhere along the Woodstock deposit exposure, at the sample locality, could material of boulder and cobble size of compositions other than coarse grained sandstone be seen.

As sandstone and volcanics are the least resistant to abrasion and breakage, of all the rock types known in this catchment, it is worth reflecting on the problem of how particles of these compositions have maintained their relatively larger grain size when compared with other compositions of greater resistance to breakage and abrasion, such as quartz and chert.

It is not thought to be a function of density differences, as these are too small between the various compositions to be significant in effecting the sorting processes.

In part, the large volcanic boulders can be explained in terms of a second source area of closer proximity to the site of deposition than the source areas of the other constituents.

For both compositions, the answer is probably a function of the complex relationship that exists between: relative abundance, availability, internal anisotrophism (the result of cleavage or bedding) original size and shape differences of the particles and fracture intensity within the source area.

For both samples, in all the phi fractions between -6ø and the pan fraction (Figures 5.11-17, inclusively), coarse grained sandstone is the major constituent and fine grained sandstone the second most abundant. This undoubtedly reflects the availability of these two rock constituents as the source area is composed predominantly of sandstones.

Comparisons, between the minor constituents of the Woodstock and Otarama samples, reveal some interesting points.

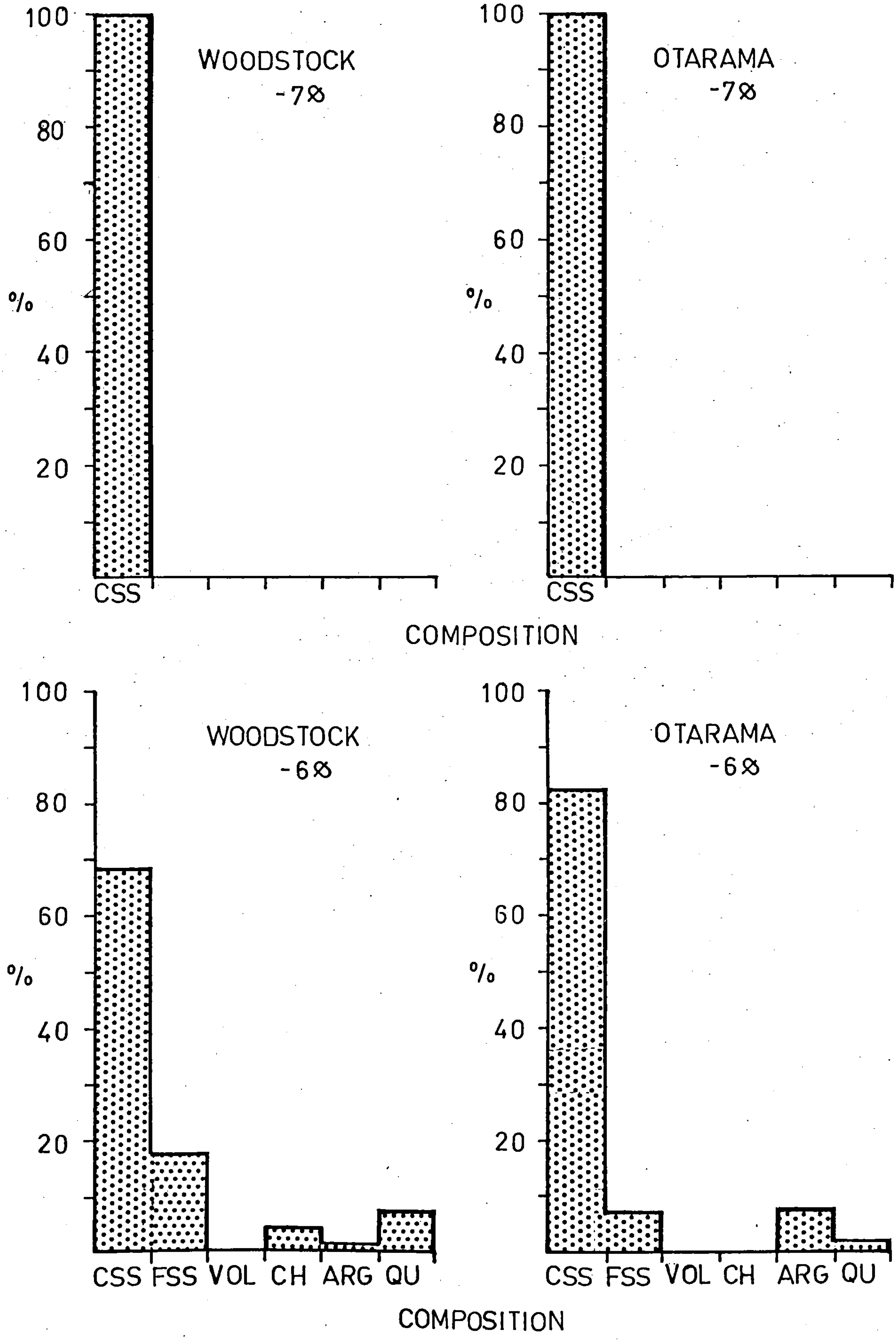


Figure 5.11 Percentages of the compositional range within the -7ϕ and -6ϕ fractions.

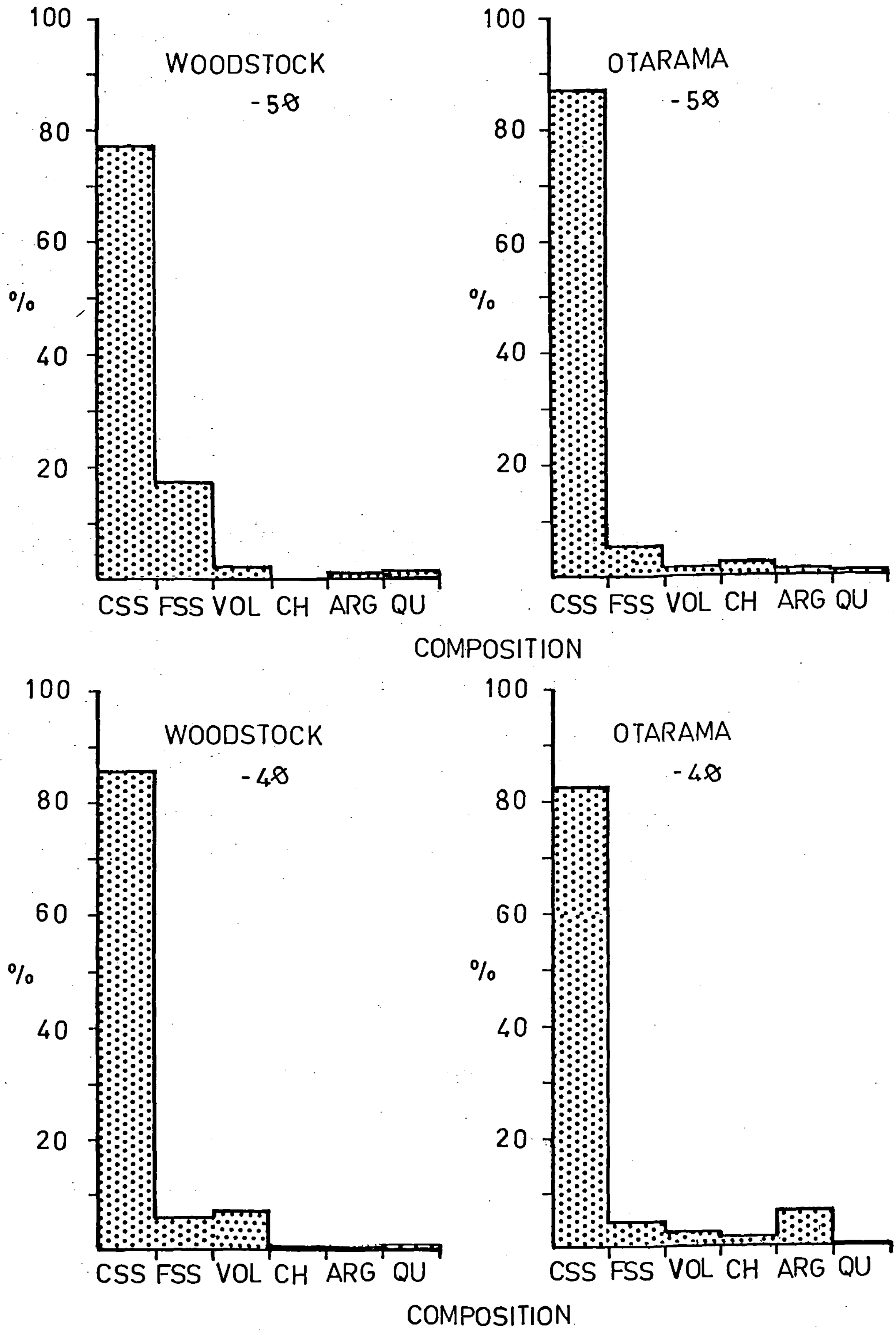


Figure 5.12 Percentages of the compositional range within the -5ϕ and -4ϕ fractions.

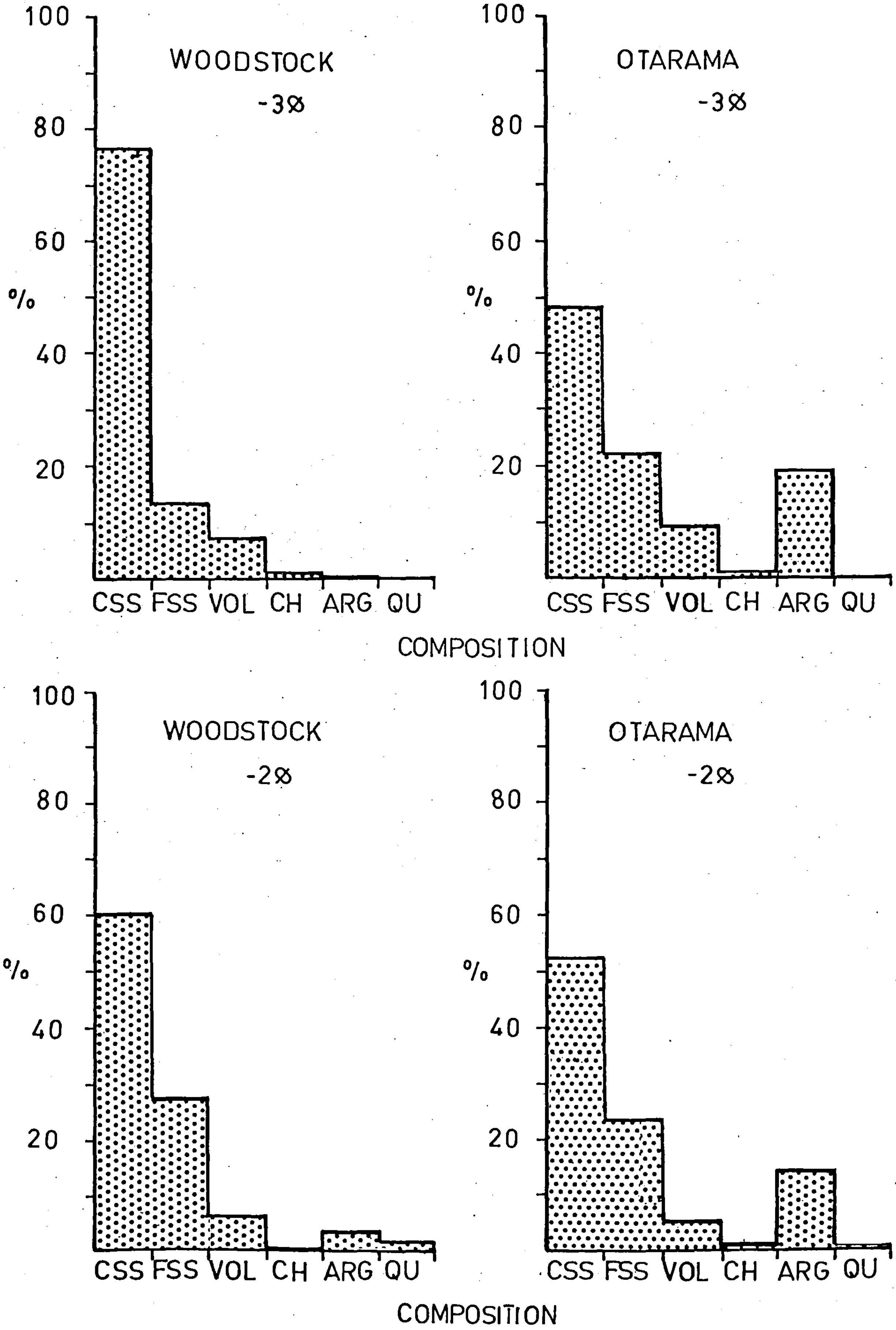


Figure 5.13 Percentages of the compositional range within the -3ϕ and -2ϕ fractions.

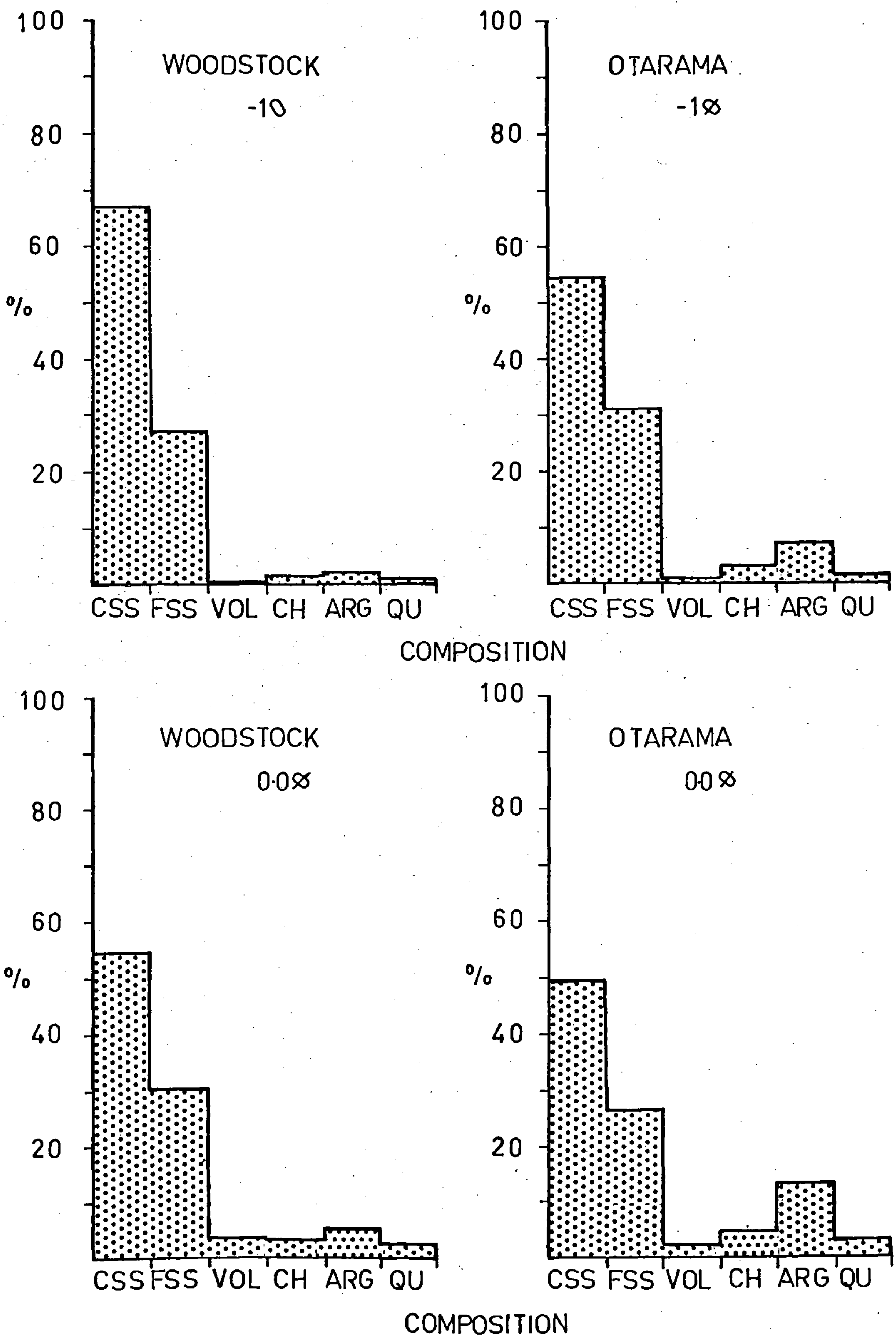


Figure 5.14 Percentages of the compositional range within the -1∅ and 0.0∅ fractions.

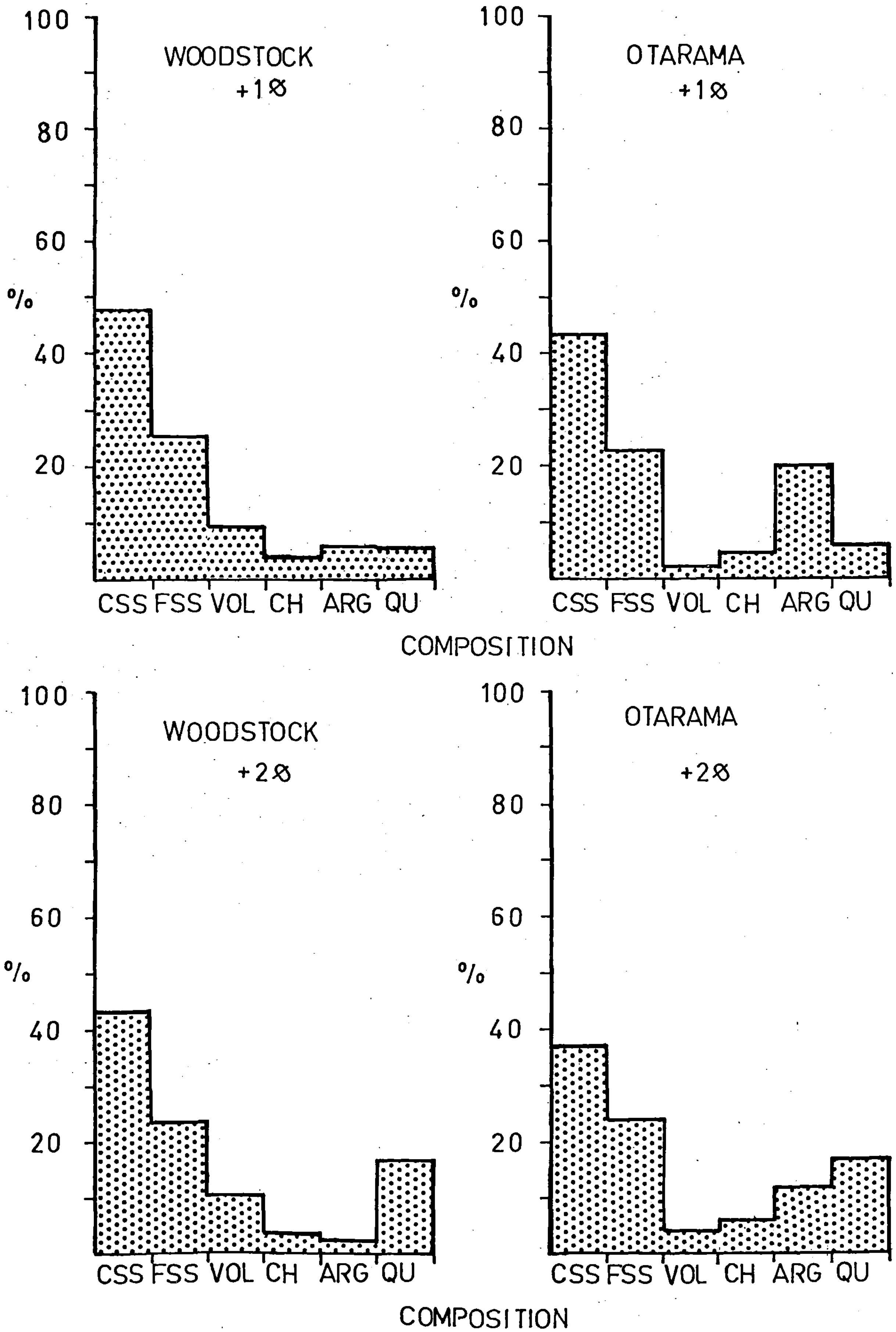


Figure 5.15 Percentages of the compositional range within the +1 and +2ø fractions.

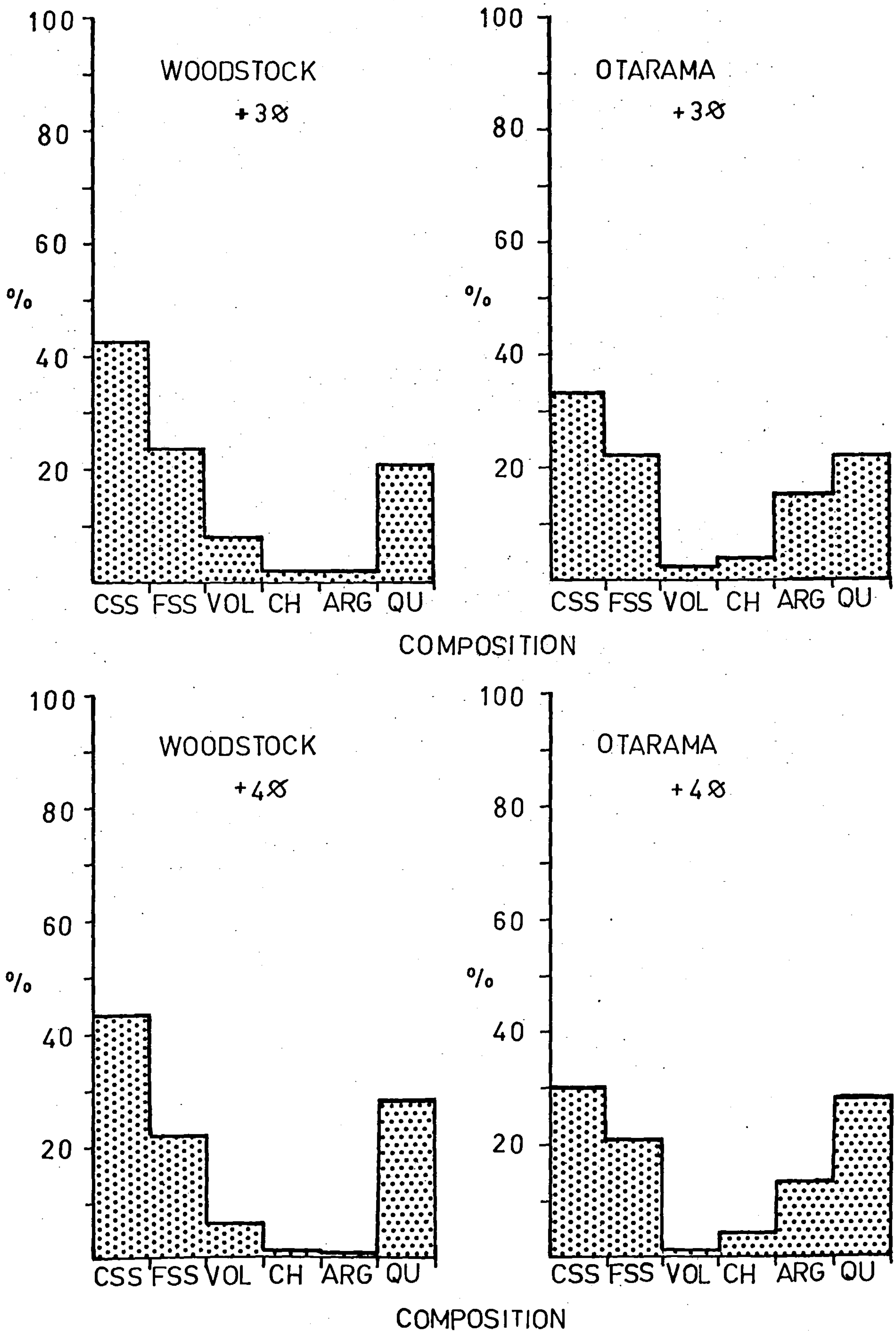


Figure 5.16 Percentages of the compositional range within the +3ø and +4ø fractions.

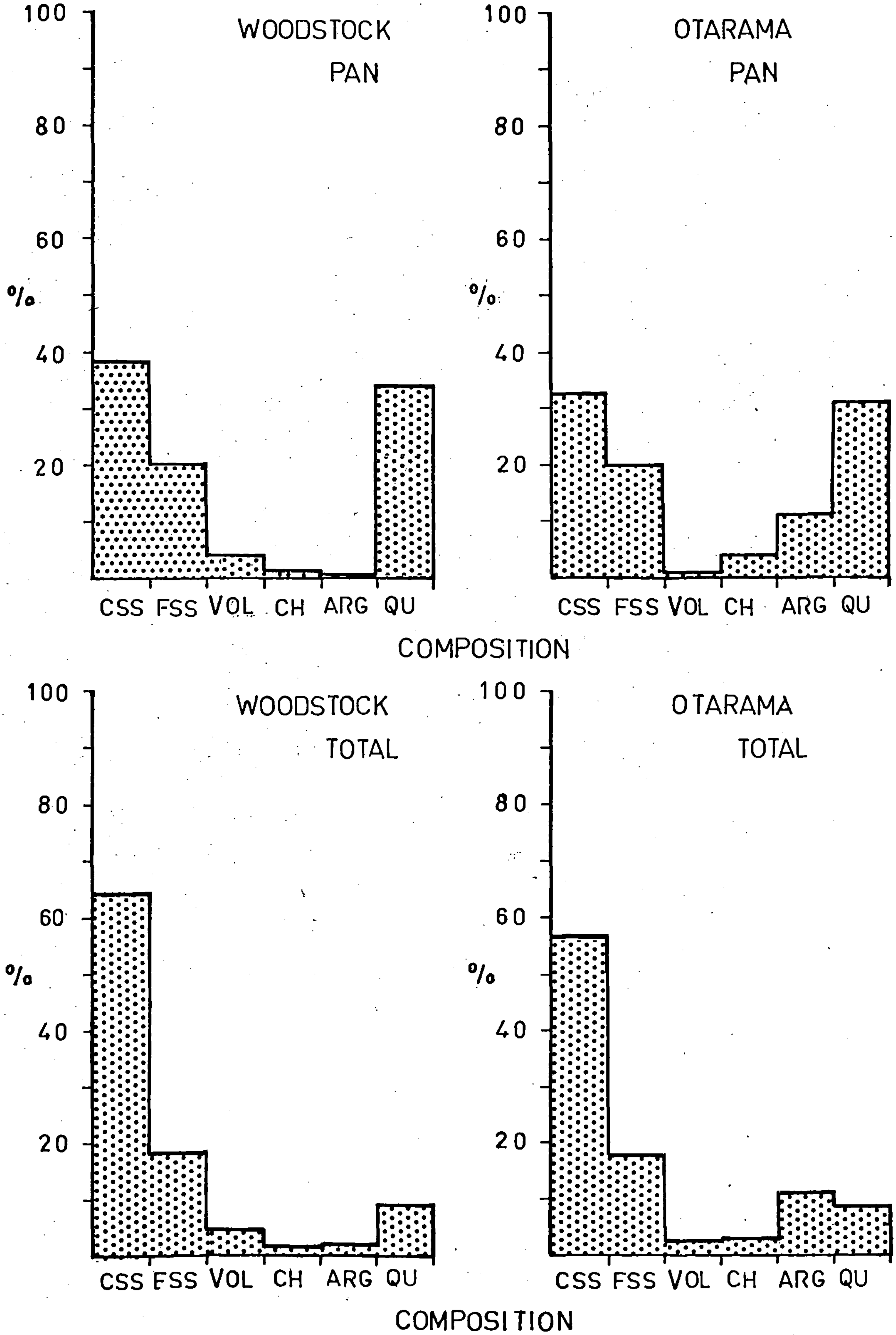


Figure 5.17 Percentages of the compositional range within the pan and total fractions.

Chert and argillite, in general, account for a higher percentage of the total composition, in each of the phi fractions between -6ø and the pan fraction, within the Otarama sample than in the equivalent phi fractions of the Woodstock sample. (Figures 5.11-17.) This is thought to be a reflection of greater availability due to the downcutting of glacial ice during Otarama times into deeper chert and argillite zones. This is particularly so for the argillite zones for many of them occur below the level of maximum downcutting of the Woodstock ice. It is also possible that much of the Chert and argillite is derived from reworked deposits of Woodstock till eroded out of the headwater region of the Kowai Catchment.

In the previous section, a second and nearer source of basalt was used to explain an anomaly in the relative grain size characteristics between chert and volcanic particles within the Otarama sample. Figurew 5:12 to 17 inclusively together with Table 9, indicate that the volcanic fraction makes up a more significant proportion of each phi fraction of the older Woodstock sample than in the equivalent phi fractions of the younger Otarama sample.

As mentioned previously this is directly related to the significant influx of basaltic particles carried down the West Branch Kowai River by Woodstock ice. During Otarama times a considerably lesser proportion of the total volcanic fraction originated from the West Branch Kowai River so that coarse grained dolerite from the Irishman Creek source dominated the deposits of Otarama times.

As noted in the previous section the quartz content shows a gradual increase, as a percentage of the total composition, with decreasing grain size. The quartz content ranges from 1-04% (-5ø fraction) to just over 30% (pan fraction) for the Otarama sample. (Figures 5.12 and 5.17, respectively.)

For the Woodstock sample the quartz content ranges from 1.69% (-5ø fraction) to approximately 34% (pan fraction). (Figures 5.12 and 5.17, respectively.)

Within the pan fraction of both samples, quartz is the second most abundant constituent.

Table 9 shows the overall percentages of the various rock constituents for both the Otarama and Woodstock samples. This data is also shown in Figure 5.17. The percentages of the breccia and miscellaneous categories was so small as to be considered insignificant.

COMPOSITION	OTARAMA	WOODSTOCK
Coarse grained sandstone	56.78%	64.28%
Fine grained sandstone	17.95	18.47
Volcanics	2.68	4.70
Chert	2.98	1.83
Argillite	10.90	2.04
Quartz	8.65	8.66
Breccia	0.04	-
Miscellaneous	0.02	0.02

Table 9 Percentages of rock constituents for the total samples of outwash gravel.

(3) Conclusions

Sandstone is the most abundant constituent in every phi fraction of both the Woodstock and Otarama samples because it is the most common lithology within the source area.

Chert and argillite comprise a greater percentage of the total Otarama, than of the total Woodstock sample. This could possibly be a result of downcutting by Otarama ice into thicker and more numerous beds of chert and argillite. However, it is more likely to be derived from the reworking of Woodstock till deposits within the upper reaches of the Kowai Catchment.

The increase in quartz content with a corresponding decrease in grain size is a direct result of the breakdown of sandstone and the subsequent release of individual quartz grains. The concentration in the finer phi sizes is also a reflection of their relative resistance to abrasion, during transportation, compared to the resistance to abrasion of the other compositions.

In view of the indication of a contribution of basalt boulders from the West Branch Kowai River during Woodstock and Otarama times, it seems probable that much of the quartz sand was also derived from the abundant, easily eroded and concentrated Tertiary deposits within this catchment. The close similarity in quartz sand distribution in both samples, particularly in the finer sizes possibly adds credence to this hypothesis.

The mean grain size differences and relative abundance of volcanic particles between the two samples can be explained in terms of source area proximity and supply.

The irregularities in the distribution of any one composition throughout the samples, or between samples is due partly to the effects of an increase or decrease of other rock types, their relative abundance and availability in the source area, and partly due to influx of new material and of course local sample variation.

From the above investigation into the composition of the Woodstock and Otarama Outwash gravels, it appears that there is no evidence of rock particles of compositions 'foreign' to the Kowai Catchment, such as limestone from the Castle Hill area or chert from the Rakaia Catchment.

This however, in the case of limestone, cannot be used as negative evidence as its absence may be related to its relatively weak resistance to both chemical and physical decomposition. It is also significant to consider the distance of transport, from source to site of deposition, (approximately 20 km), together with the age of the deposits, (early Late Pleistocene).

Chert, on the other hand, has a greater degree of resistance to abrasion and chemical decomposition. Not only is there an absence of bedrock chert within the West Branch Kowai and Thirteen Mile Bush Stream Catchments, but there is also no sign of a significant amount of chert that may have been transported into these Catchments by glacier ice of the Woodstock Glacial Advance, from the Rakaia Catchment. The only significant source of chert is therefore from within the headwaters of the Kowai River, flanking the slopes of Mount Torlesse. The sources of all other lithologies are known to occur within the Kowai and tributary river systems. It has therefore been assumed for the purposes of this study that all the glacial deposits in the Kowai Cathcment originated within this catchment.

One final point is that the slight variations in the percentages of the minor rock constituents between samples, is not sufficient to explain the colour variation that exists between the Woodstock and Otarama deposits. It is therefore concluded that the contrasting colours are a reflection of the intensity and duration of weathering processes, essentially caused by the percolating of solutions through the in situ deposits.

VIII SPHERICITY

(1) Definition

"Sphericity states quantitatively how nearly equal the three dimensions of an object are." (Folk, 1968.)

"Form and sphericity are chiefly the result of two factors:-

(a) internal anisotrophism (the result of bedding, schistosity or cleavage in most cases, but directional hardness may possibly be important in the cases of quartz.

(b) original shape of the particle (such as joint blocks, or platy quartz grains from schist). This is modified to some extent by abrasion, but few adequate studies have been made."

(Folk, 1968.)

(2) Method of Analysis

To determine if there were any significant sphericity differences between the Woodstock and Otarama Outwash gravels, three diameters, designated as (a), (b) and (c) for the long, intermediate and short axes respectively, were measured with a pair of metal calipers. Where possible every pebble, cobble and boulder was taken into account. The material analysed ranged from -3ϕ to -7ϕ in size. The results were recorded as follows:

Pebble	Long Diameter in mm (a)	Intermediate Diameter (b)	Short Diameter (c)	b/a	c/b	ψ
1	45	38	17	0.84	0.45	0.68
2	51	48	39	.94	.81	.90
3	48	24	22	.50	.92	.62

Table 10 Arrangement of data for intercept sphericity.

Two ratios were then determined and entered in adjacent columns. The first is the ratio of the intermediate to the long diameter (b/a), and the second is the ratio of the short to the intermediate diameter (c/b).

To determine the sphericity, these ratios are laid off on the axes of the chart in Figure 5.19, and where the values intersect in the diagram the sphericity may be read off to the nearest two hundredths.

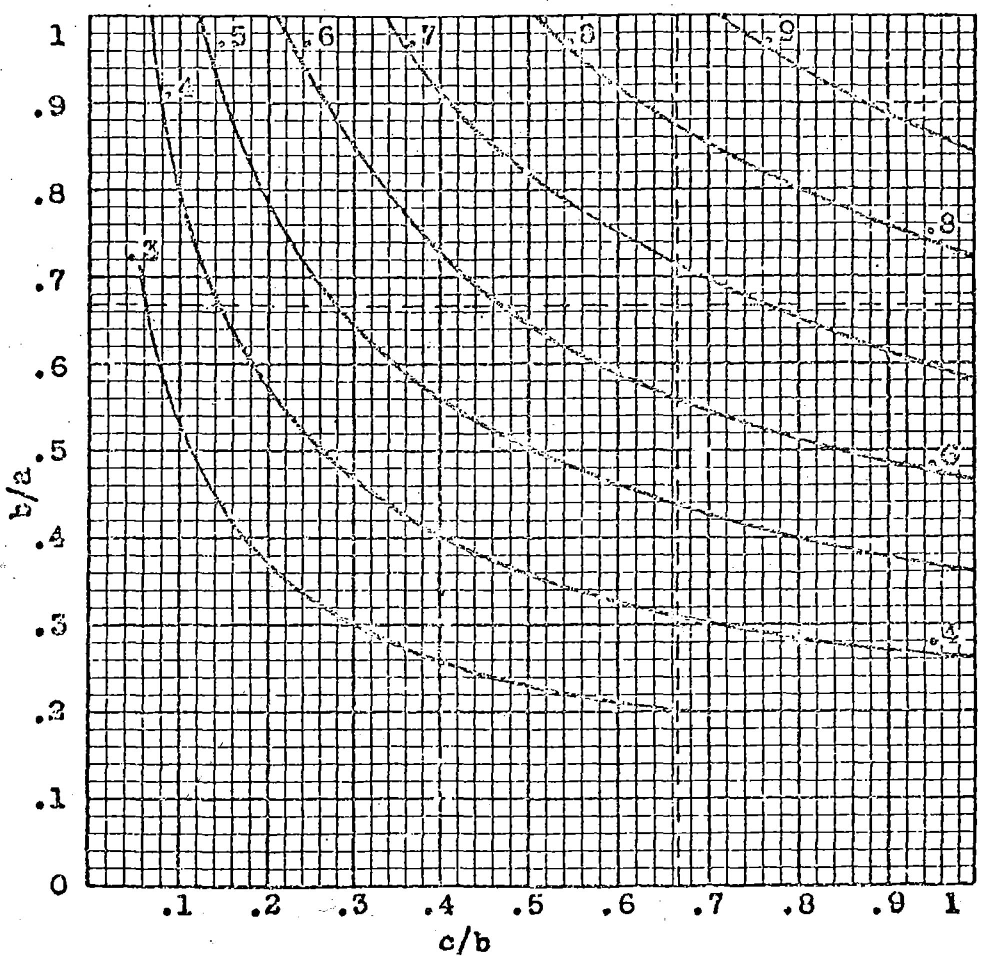


Figure 5.18 Detailed chart for determining sphericity (from Krumbein W.C. 1941)

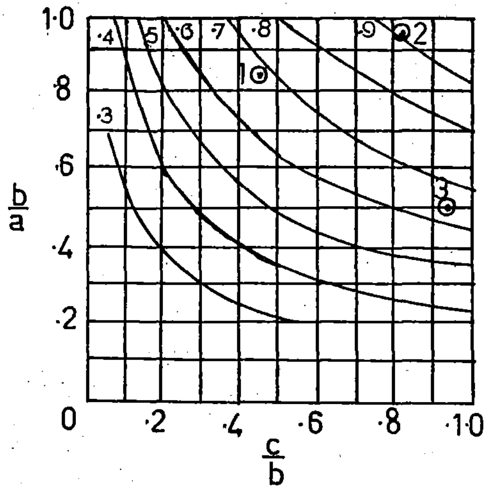


Figure 5.19 Chart for determining sphericity. The curves represent lines of equal sphericity. The numbered circles refer to the examples in Table 10. (From Krumbein, 1941.)

Figure 5.19 shows the location of the three pebbles in Table 10, and the corresponding interpolated sphericities are entered in the last column of the table.

An enlargement of Figure 5.18, upon which overlays of tracing paper were laid, was used to determine the interpolated sphericity values for every rock particle of each composition, for the range of phi fractions between -3ϕ amd -7ϕ. An overlay for each phi fraction, regardless of composition, was compiled. (Figures 5.20 and 5.21.) An overlay of the total number of particles measured, regardless of size, for each of the Woodstock and Otarama samples was also compiled. (Figure 5.21.) When all the particles had been plotted, the number of particles within each sphericity category, between the range of 0.2 ψ and 1.0 ψ, were counted, from which a histogram and cumulative curve showing percentage sphericity against sphericity values was drawn up. (Figure 5.22.) The data for this figure is to be found in Table 12. It was attempted only for the plots showing the total number of particles measured, for both the Woodstock and Otarama samples.

From the sphericity values, the mean sphericity and standard deviation was calculated for:

(a) each composition over the full range of phi fractions,

(b) each phi fraction,

and (c) the total samples. (Table 11.)

Table 13 shows data selected from Table 11 and arranged so as to enable the mean of the mean sphericity values for each composition, irrespective of phi size, to be calculated.

Because many of the phi fractions had fewer than thirty particles of some of the rock compositions, a formula for adjusting the calculated standard deviation was used whereby the standard deviation calculated from the formula

$$\sqrt{\frac{\Sigma X^2 - N\bar{X}^2}{N}}$$

was multiplied by

$$\sqrt{\frac{n}{n - 1}}$$

Phi Size	Composition	Number of Pebbles Measured		Mean Sphericity		SD $\sqrt{\frac{\Sigma x^2 - N\bar{x}^2}{N}}$	
		Otarama	Woodstock	Otarama	Woodstock	Otarama	Woodstock
-7ø	Coarse grained sandstone	17	26	0.65	0.64	0.076	0.118
Mean Sphericity for -7ø				0.65	0.64		
-6ø	Coarse grained sandstone	150	77	0.68	0.69	0.103	0.109
	Fine sandstone	13	20	0.65	0.66	0.080	0.045
	Argillite	14	2	0.69	0.70	0.089	0.042
	Quartz	4	8	0.68	0.69	0.090	0.075
	Chert	–	5	–	0.64	–	0.085
Mean Sphericity for -6ø				0.68	0.69		
-5ø	Coarse grained sandstone	252	138	0.67	0.68	0.108	0.099
	Fine grained sandstone	17	31	0.65	0.65	0.073	0.024
	Argillite	4	2	0.73	0.69	0.076	0.020
	Quartz	3	3	0.68	0.65	0.185	0.082
	Volcanics	5	4	0.63	0.64	0.081	0.017
	Chert	7	–	0.70	–	0.114	–
	Breccia	1	–	0.65	–	–	–
Mean Sphericity for -5ø				0.67	0.66		
-4ø	Coarse grained sandstone	155	153	0.69	0.70	0.103	0.012
	Fine grained sandstone	50	70	0.64	0.65	0.095	0.096
	Argillite	40	9	0.67	0.70	0.092	0.066
	Quartz	6	12	0.66	0.72	0.064	0.091
	Volcanics	33	56	0.70	0.70	0.100	0.127
	Chert	33	9	0.70	0.73	0.099	0.109
	Breccia	5	3	0.65	0.76	0.090	0.074
	Miscellaneous	5	–	0.62	–	0.093	–
Mean Sphericity for -4ø				0.67	0.70		
-3ø	Coarse grained sandstone	50	100	0.69	0.66	0.111	0.016
	Fine grained sandstone	50	100	0.64	0.66	0.105	0.113
	Argillite	50	10	0.63	0.69	0.113	0.076
	Quartz	–	10	–	0.77	–	0.079
	Volcanics	50	100	0.70	0.70	0.113	0.097
	Chert	50	30	0.69	0.69	0.104	0.109
Mean Sphericity for -3ø				0.67	0.70		
Mean Sphericity for total sample				0.67	0.68		

TABLE 11: Number of particles measured, mean sphericity and standard deviation for each composition.

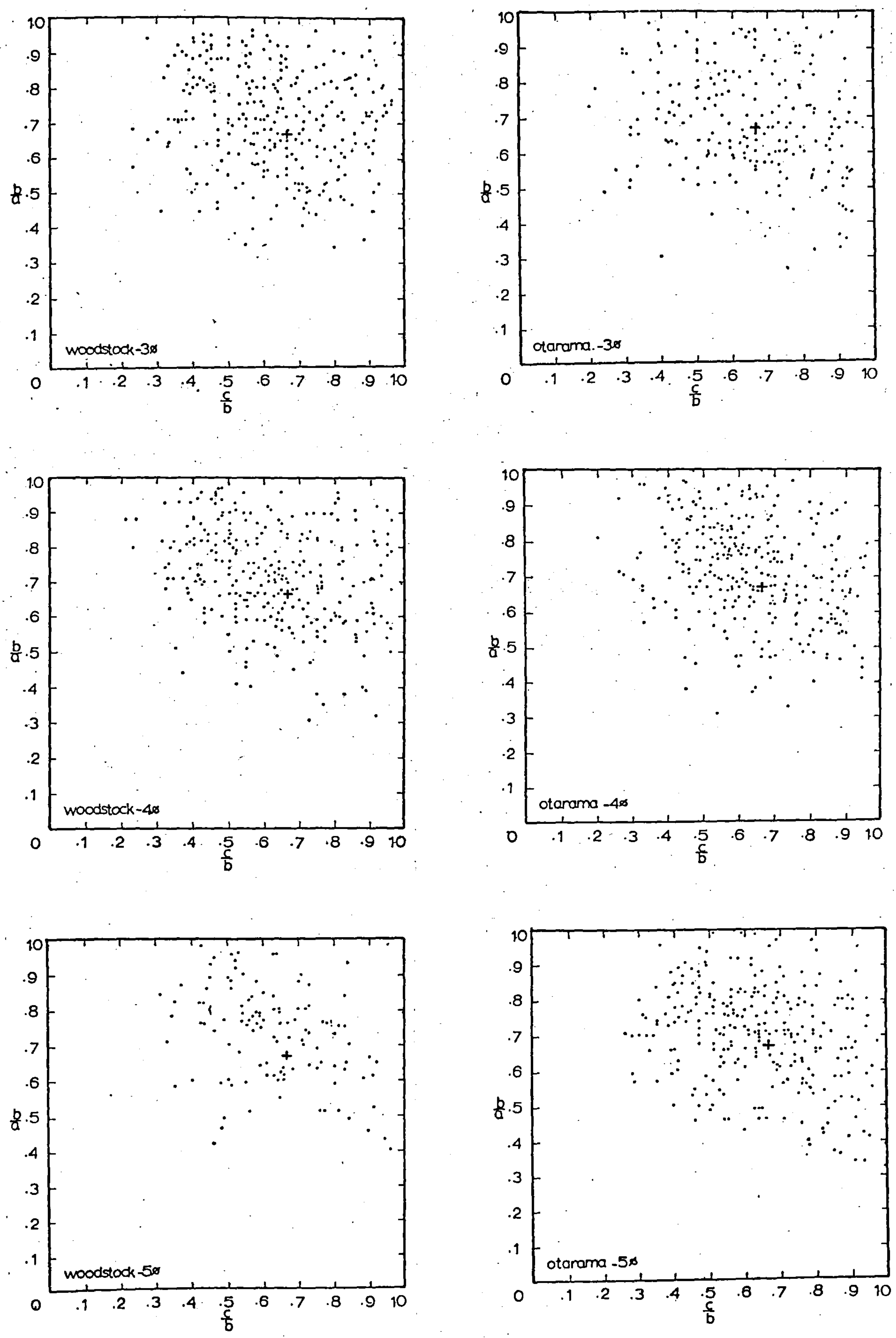


Figure 5.20 Sphericity charts showing the distribution of all the particles measured and plotted within each phi fraction.

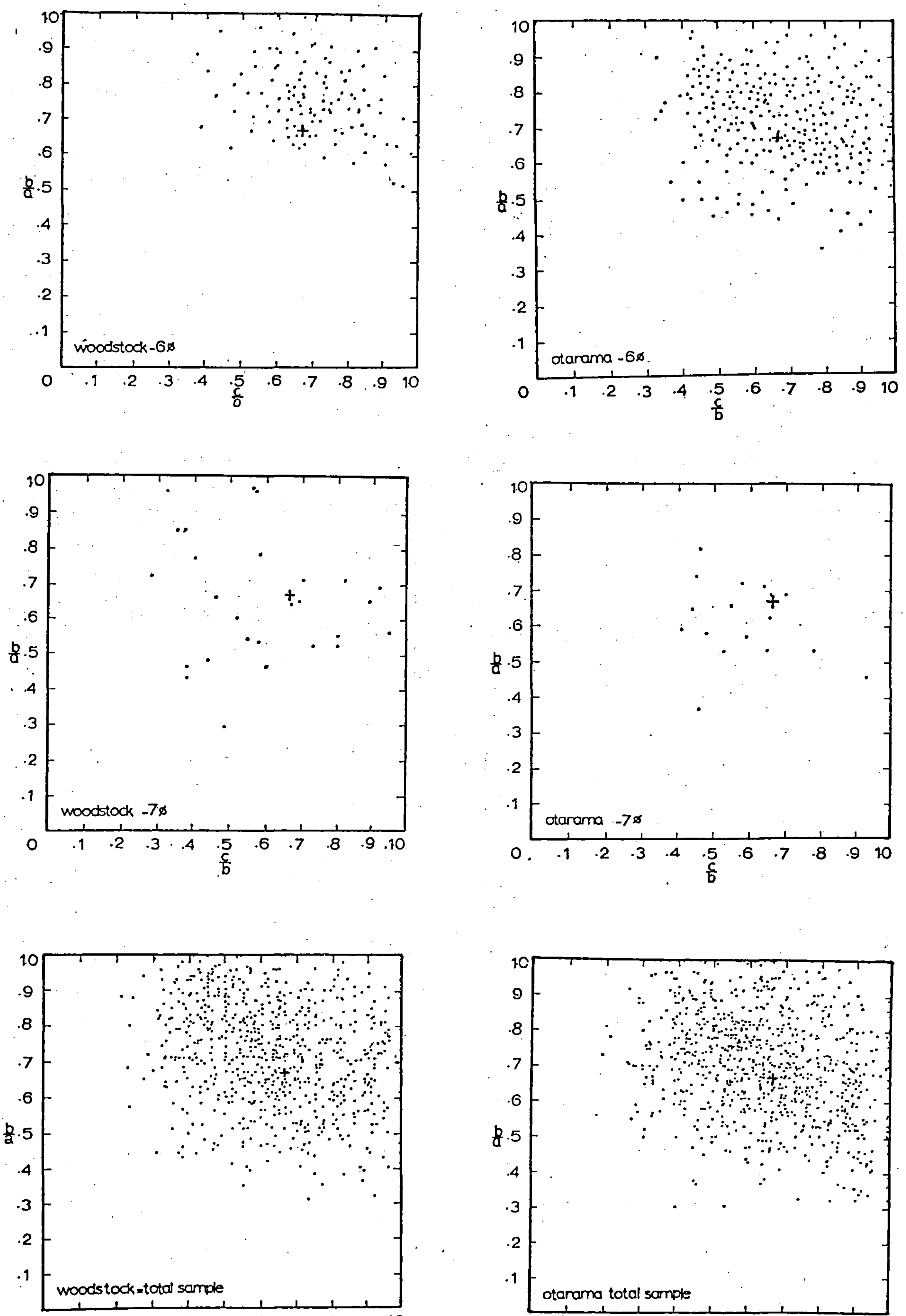


Figure 5.21 Sphericity charts showing the distribution of all the particles measured and plotted within each phi fraction.

The results of those computations are tabulated in Table 11.

Contouring of the sphericity plots was attempted to see where the highest concentration of points occurred with respect to the sphericity values. This was achieved by using a one centimeter grid underlay in conjunction with a metal plate. The plate which measured 4 cm x 4 cm had a two centimeter diameter hole cut out of it. The plate was systematically moved along the grid lines until two intersecting lines appeared at the centre of the hole. The number of points falling within this area were counted and the figure recorded at the intersection of the grid lines. Contour lines were drawn connecting points of equal value. (Figure 5.23.) This was attempted only for the plots showing the total number of particles measured.

(3) <u>Results</u>

In every case, the concentration of points falls within the same quadrant, with slight variations being in the degree of spread of the points. (Figures 5.20 and 5.21.) When the sphericity values are arranged into sphericity units, ranging from 0.2 ψ to 1.0 ψ, the similarity in the degree and distribution of sphericity attained by the particles within the Woodstock and Otarama deposits, is readily apparent.

For both samples, the mode and median fall within the 0.6ψ to 0.7ψ sphericity value range. One noticeable difference between the two samples is the percentage of particles within the mode sphericity value range. (Figure 5.22.) The Otarama sample contains 5% more particles within this range than does the Woodstock sample. Variations in the percentage of particles within each sphericity value unit, between the samples is reflected by changes in the slope of the cumulative curve. (Figure 5.22.)

To determine if any correlation existed between the degree of sphericity attained and grain size, the mean sphericity value for each phi fraction was determined. The mean of the total sample was then calculated from the sum of these mean values. (Table 11.) Neither the mean for the phi fractions nor the total mean indicate any differences in sphericity between the two samples. The mean sphericity value for the total Otarama sample being 0.67ψ and that for the Woodstock sample being 0.68ψ.

In nearly every case the standard deviation for each composition, irrespective of grain size averages approximately 0.1. (Table 11.) This indicates an error of between 15% to 17% for sphericity values ranging from 0.65ψ to 0.70ψ. The standard deviation between the means of each phi is 0.054, for the Otarama sample, and 0.032 for the Woodstock sample. This indicates that at the 95% level of confidence, all the particles within the Otarama

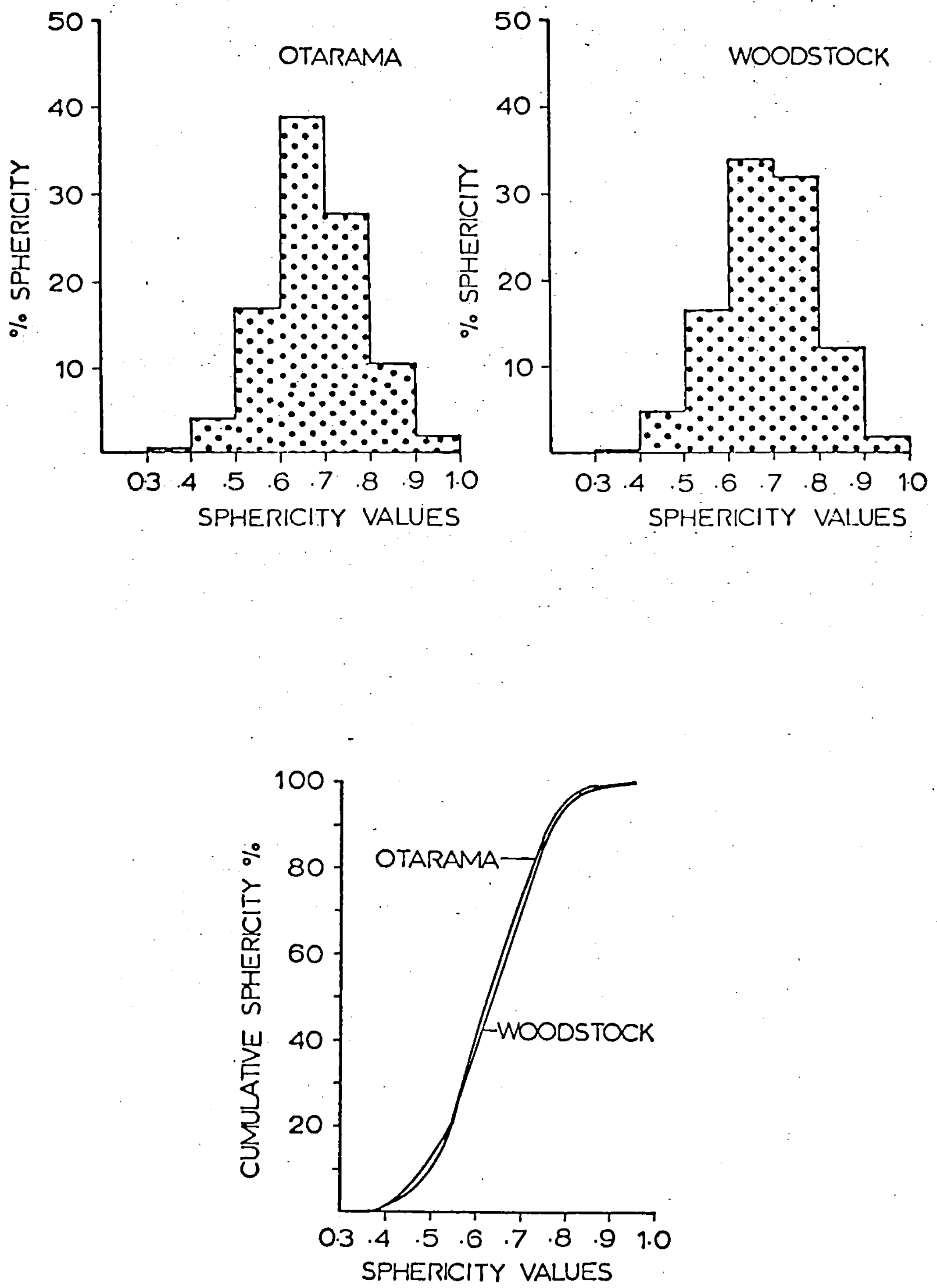


Figure 5.22 Percent and cumulative percent for the sphericity value range between 0.3 and 1.0.

sample have sphericity values within the range of 0.60ψ and 0.74ψ and those for the Woodstock sample should fall within the sphericity value range of 0.64ψ to 0.72ψ.

To determine if there was any correlation between the degree of sphericity attained and composition, irrespective of grain size, the mean sphericity values for each composition (Table 11), were re-arranged (Table 13) so as to enable the computation of the mean of all the means for each composition. Once again the differences in sphericity between the compositions in the two samples are very slight, being in the order of 0.01ψ and less. These differences are not thought to be significant.

Contouring of the sphericity plots was attempted for each of the phi fractions, for both samples, however, they are not included here as no recognisable pattern emerged on account of their being too few points on each plot. Only the plots showing the distribution of the total number of particles measured, showed a recognisable contour pattern. (Figure 5.23.)

The contour patterns for the two samples are practically identical, with a high concentration of 52 particles and 44 particles (Otarama and Woodstock samples respectively), each with an average sphericity value of 0.7ψ . The Otarama sample has an additional

	WOODSTOCK		OTARAMA	
Sphericity Values	Percent	Cum %	Percent	Cum %
0.2 to 0.3	0.0	0.0	0.0	0.0
0.3 to 0.4	0.1	0.1	0.4	0.4
0.4 to 0.5	4.7	4.8	3.8	4.2
0.5 to 0.6	16.2	21.0	16.8	21.0
0.6 to 0.7	33.8	54.8	38.8	59.8
0.7 to 0.8	31.6	86.4	27.8	87.6
0.8 to 0.9	11.9	98.3	10.4	98.0
0.9 to 1.0	1.7	100	2.0	100

TABLE 12: Percent and cumulative percent sphericity.

Sample	Phi Sizes	COMPOSITION					
		Coarse Sand-stone	Fine Sand-stone	Chert	Argillite	Volcanics	Quartz
	-7	0.64	-	-	-	-	-
	-6	0.69	0.66	0.69	0.70	-	0.69
WOODSTOCK	-5	0.68	0.65	-	0.69	0.64	0.65
	-4	0.70	0.65	0.73	0.70	0.70	0.72
	-3	0.66	0.66	0.69	0.69	0.70	0.77
Total Mean		0.674	0.655	0.700	0.695	0.680	0.707
	-7	0.65	-	-	-	-	-
	-6	0.68	0.65	-	0.69	-	0.68
OTARAMA	-5	0.67	0.65	0.70	0.70	0.63	0.68
	-4	0.69	0.64	0.70	0.67	0.70	0.66
	-3	0.69	0.64	0.69	0.63	0.70	-
Total Mean		0.676	0.645	0.696	0.672	0.676	0.673

TABLE 13: Mean sphericity values for each composition.

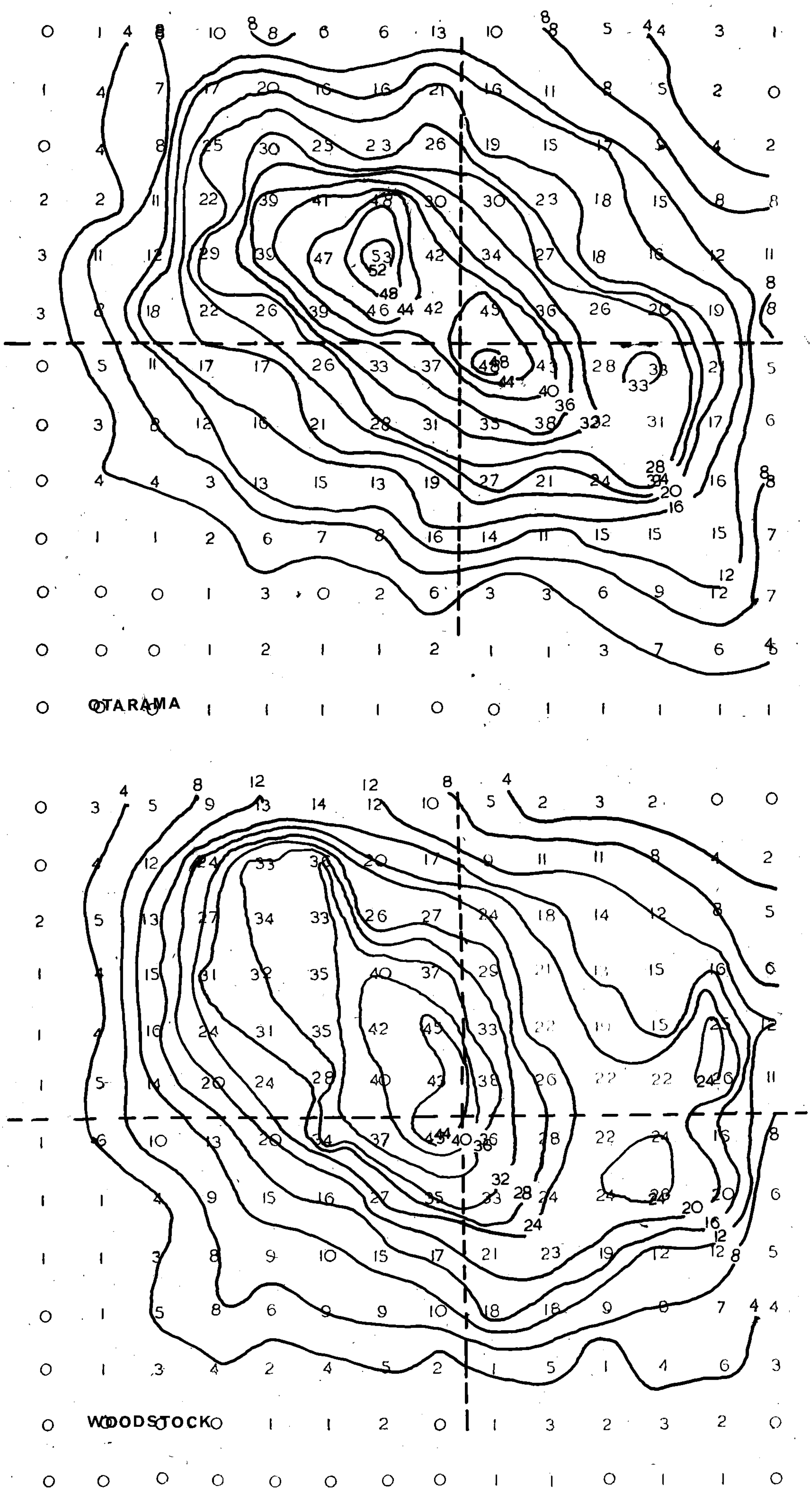


Figure 5.23 Contours of sphericity plots for the total samples.

high concentration of 48 particles with an average sphericity value of 0.67 ψ.

(4) Conclusions

The Woodstock and Otarama outwash gravels have attained a very similar degree of sphericity. Good evidence exists to show that glacial transport can and does enhance the development of a high degree of sphericity if the stone escapes crushing, and that the observed degrees of sphericity are chiefly the effects of glacial abrasion. Once a high degree of sphericity is attained, the likelihood of crushing would presumably be greatly reduced. (Holmes, 1960.)

Although no indication of the relationship between sphericity and grain size, and sphericity and composition is apparent over the phi size range considered here in either sample, sphericity is known to be a "complex function of rock types, pebble size and distance". (Sneed and Folk; 1958.)

Although no measurements were made for the phi size range smaller than -2ϕ, it was noted that grains became increasingly more angular with a decrease in grain size, and increase in compositions other than sandstone.

IX SHAPE FACTOR

(1) General Introduction

In addition to the abrasional environment the "original shape" of the rock fragment, when removed from the bedrock, also helps to determine its "final" shape. It is reasonable to anticipate that texturally anisotropic rocks will fracture into less spherical fragments than isotropic rocks. Foliation and small scale joint patterns abound in hard specimens and it was therefore assumed that the majority of rocks were anisotropic.

(2) Relationship Between Sphericity and Zingg Shape Classes

Holmes's (1960) method and data are most relevant to this study as a means of comparison but unfortunately there is a difficulty in that his pebble shape groups (ovoid, wedgeform, rhomboid) are not likely to have the same meaning to different people. This difficulty was overcome by using the Zingg (1935) shape classification which has become a quantitative standard for representing pebble shapes.

Zingg developed a classification of pebble shapes based on the b/a and c/b ratios. (Table 14.)

Class	b/a	c/b	Shape
I	$>2/3$	$<2/3$	Discs
II	$>2/3$	$>2/3$	Spherical
III	$<2/3$	$<2/3$	Blades
IV	$<2/3$	$>2/3$	Rod like

Table 14 Zingg's classification of particle shape.

Krumbein (1941) merely combined figures 5.18 and 5.24. In as much as the intercept sphericity is based on any values of b/a and c/b, these ratios may be plotted where upon not only may the sphericity be read, but the pebbles are automatically classified according to Zingg. This method of shape determination, however, does not lend itself to small particles in which the three axes cannot be separately measured hence it was only attempted on the larger phi sizes ranging from -3.0ϕ to -7.0ϕ.

When it was thought that the shape factor was related to grain size or composition, comparisons between these properties were made.

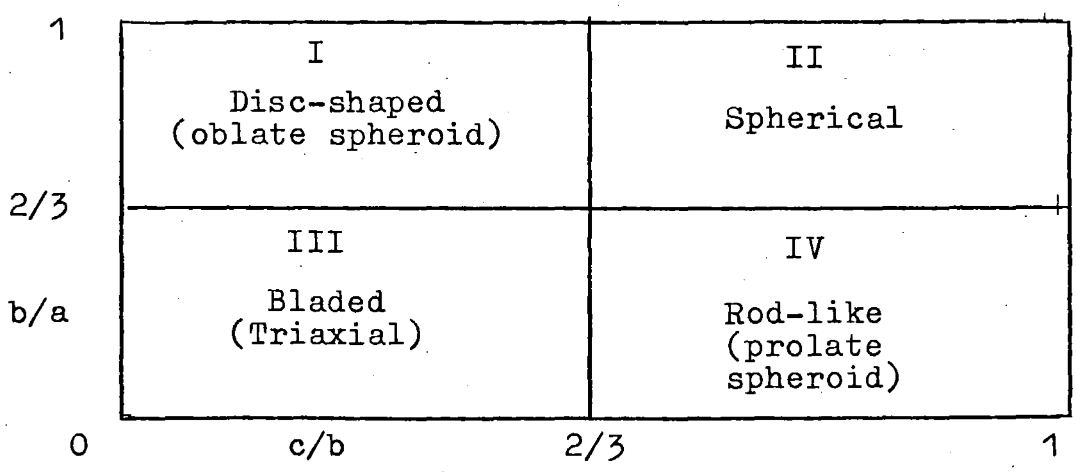


Figure 5.24 Zingg's classification of pebble shapes (see Table 14).

(3) <u>Results</u>

Disc-shaped particles dominate almost every phi fraction between -3ø and -5ø, (Figures 5.25 to 5.27) in both samples. In contrast the -7ø fraction is dominated by blade-shaped particles. (Figure 5.25.) Blade-shaped particles only form a minor percentage of the remainder of the phi fractions. This dominance of blade-shaped particles in the -7ø fraction is in part a reflection of the small number of particles within this fraction (Table 15). It is not thought to be a reflection of composition or the grain size of the particles. Overall, the order of dominance of particle shapes in terms of percentage of the total number of particles measured, for both samples, is disc, spherical, rod and blade (Table 16).

> Drake (1972) . . . "Suggests that crushing and abrasion are the dominant factors controlling final shape of the pebbles. With regard to crushing, the elongate pebbles (blades and rods) would clearly be most susceptible to fracture and the spheres the least susceptible. Hence, blades are more susceptible to crushing and abrasion and are destroyed most rapidly. Spheres are least susceptible to crushing and are actually produced by abrasion and so are the most durable shape. Rods are susceptible to crushing but their properties are little affected by abrasion (Drake; 1970), so their numbers increase slightly. Discs, then, are slightly favoured by combined crushing and abrasion because if the elongate pebbles (rods and blades) are most easily destroyed, then this can increase the relative proportions of discs as well as spheres.

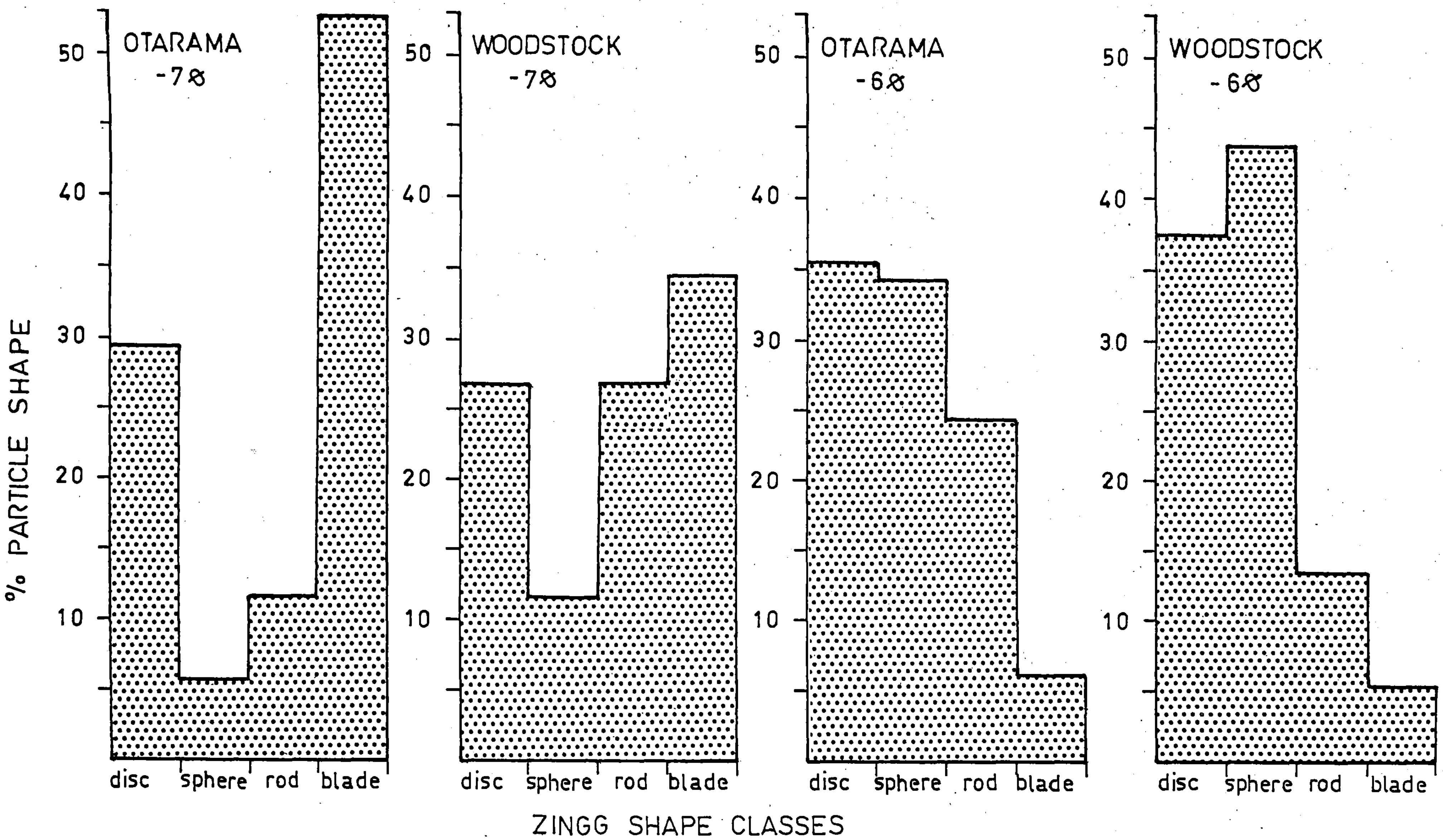


Figure 5.25 Percentages of particles within each of the Zingg shape classes for the -7∅ and -6∅ fractions.

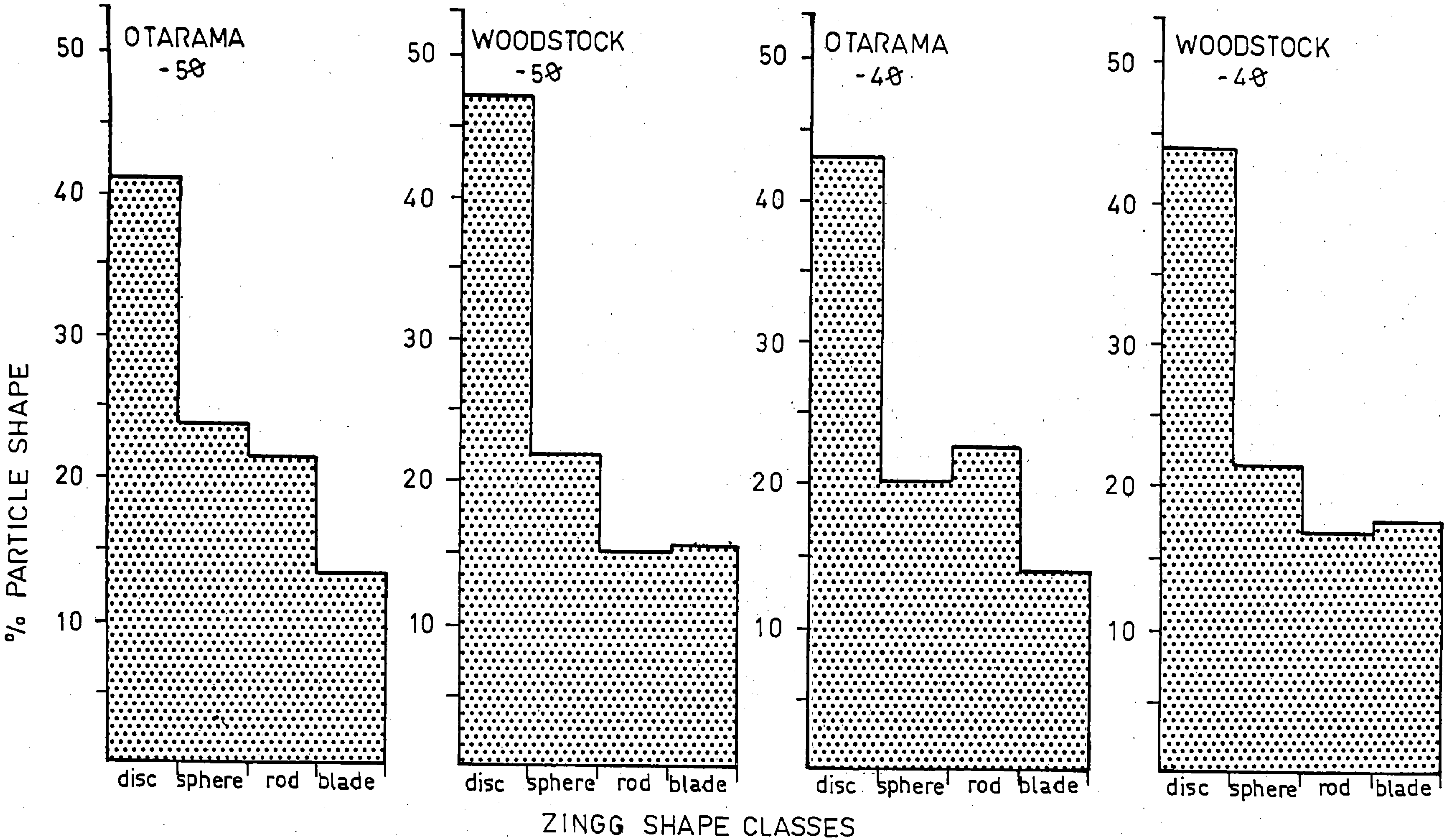


Figure 5.26 Percentages of particles within each of the Zingg shape classes for the -5ϕ and -4ϕ fractions.

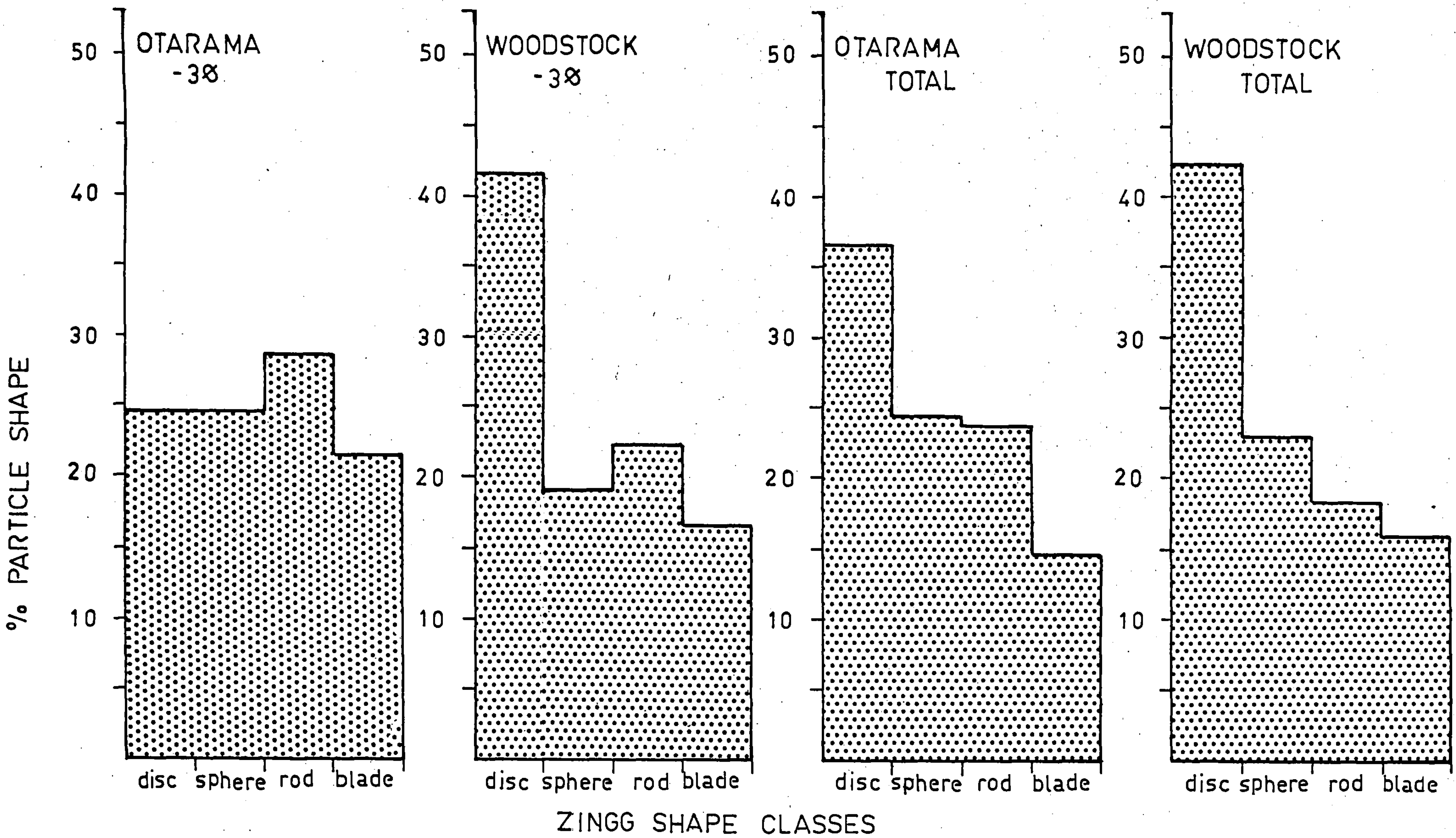


Figure 5.27 Percentages of particles within each of the Zingg shape classes for the -3ø and total fraction.

> From the above interpretation, crushing and abrasion appear to be about equally effective in destroying pebbles. Pebble shape evolution is a relatively slow process compared to rates of crushing and abrasion and many generations of crushing and abrasion are necessary to alter the net proportions of pebble shapes."
>
> (Drake; 1972.)

Figure 23 shows the concentrations of particles in relation to the four Zingg shape classes, for both the Woodstock and Otarama samples. For the Otarama sample the highest concentration of 52 particles lies within the disc-shaped category, while a second concentration of 48 particles falls within the rod-like shape category. Both concentrations lie within the 0.6 ψ to 0.7 ψ sphericity value range.

Only one concentration of particles of any significance within the Woodstock sample is distributed between the disc-shaped and blade-shaped categories. The concentrations of particles within the Woodstock sample are not as high as those within the Otarama sample because of the greater range of sphericity values in the former sample.

When each particle shape category is analysed individually by expressing the distribution of the total number of particles of that shape as a percentage for each of the phi sizes, it is apparent that in most cases the trend of increasing percentages towards

Phi Size	Composition	Zingg Particle Shape Classification								Number of particles measured	
		Disc		Spherical		Blade		Rod like			
		Ot	Wdst	Ot	Wdst	Ot	Wdst	Ot	Wdst	Ot	Wdst
-7ø	Coarse gained sandstone	5	7	1	3	9	9	2	7	17	26
Total		5	7	1	3	9	9	2	7	17	26
-6ø	Coarse grained sandstone	54	36	45	25	11	6	40	10	150	77
	Fine grained sandstone	4	4	8	11	-	-	1	5	13	20
	Chert	-	-	-	5	-	-	-	-	-	5
	Argillite	4	1	8	1	-	-	2	-	14	2
	Quartz	2	1	1	7	-	-	1	-	4	8
Total		64	42	62	49	11	6	44	15	181	112
-5ø	Coarse grained sandstone	108	64	55	27	38	27	51	20	252	138
	Fine grained sandstone	4	15	9	10	1	1	3	5	17	31
	Chert	2	-	3	-	-	-	2	-	7	-
	Argillite	2	2	1	-	-	-	1	-	4	2
	Quartz	1	1	1	1	-	-	1	1	3	3
	Volcanics	1	2	-	1	-	-	4	1	5	4
	Breccia	1	-	-	-	-	-	-	-	1	-
Total		119	84	69	39	39	28	62	27	289	178
-4ø	Coarse grained sandstone	62	62	35	35	24	30	34	26	155	153
	Fine grained sandstone	23	32	7	10	12	9	8	19	50	70
	Chert	15	6	9	2	4	1	5	-	33	9
	Argillite	18	5	7	2	3	2	12	-	40	9
	Quartz	3	3	-	5	1	1	2	3	6	12
	Volcanics	17	28	7	13	1	11	8	4	33	56
	Breccia	2	1	-	-	-	1	3	1	5	3
	Miscellaneous	1	-	1	-	1	-	2	-	5	-
Total		141	137	66	67	46	55	74	53	327	312
-3ø	Coarse grained sandstone	16	39	17	16	6	16	11	29	50	100
	Fine grained sandstone	12	41	7	20	14	19	17	20	50	100
	Chert	12	13	16	4	8	7	14	6	50	30
	Argillite	15	3	6	3	10	1	19	3	50	10
	Quartz	-	2	-	6	-	-	-	2	-	10
	Volcanics	7	48	16	18	16	15	11	18	50	100
Total		62	146	62	67	54	59	72	78	250	350
Sample Total		391	416	260	225	159	157	254	180	1064	978

TABLE 15: Number of particles measured within each phi unit, for each composition, and for the four Zingg particle shape classes.

Phi Size	Zingg Spherical Shape Categories								Number of particles measured	
	Disc		Spherical		Rod-like		Blade			
	Ot	Wdst	Ot	Wdst	Ot	Wdst	Ot	Wdst	Ot	Wdst
-7	29.41	26.92	5.88	11.54	11.76	26.92	52.94	34.62	17	26
-6	35.36	37.50	34.25	43.75	24.31	13.39	6.08	5.36	181	112
-5	41.18	47.19	23.88	21.91	21.45	15.17	13.49	15.73	289	178
-4	43.12	43.91	20.18	21.47	22.63	16.99	14.07	17.63	327	312
-3	24.80	41.71	24.80	19.14	28.80	22.29	21.60	16.86	250	350
Total	36.75	42.54	24.44	23.01	23.87	18.40	14.94	16.05	1064	978

TABLE 16: Percentage of particles within each Zingg particle shape category for the various phi fractions and total sample. This data is shown in figures 25 to 27.

Phi Size	Zingg Spherical Shape Categories							
	Disc		Spherical		Rod-like		Blade	
	Ot	Wdst	Ot	Wdst	Ot	Wdst	Ot	Wdst
-7	1.28	1.68	0.38	1.33	0.79	3.89	5.66	5.73
-6	16.37	10.10	23.85	21.78	17.32	8.33	6.92	3.82
-5	30.43	20.19	26.54	17.33	24.41	15.00	24.53	17.83
-4	36.06	32.93	25.38	29.78	29.13	29.44	28.93	35.03
-3	15.86	35.10	23.85	29.78	28.35	43.33	33.96	37.58
	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %

TABLE 17: Percentage of each Zingg particle shape, calculated from the total number of particles of that shape within each sample, for the various phi fractions. This data is shown in figures 28 and 29.

(A)

(B)

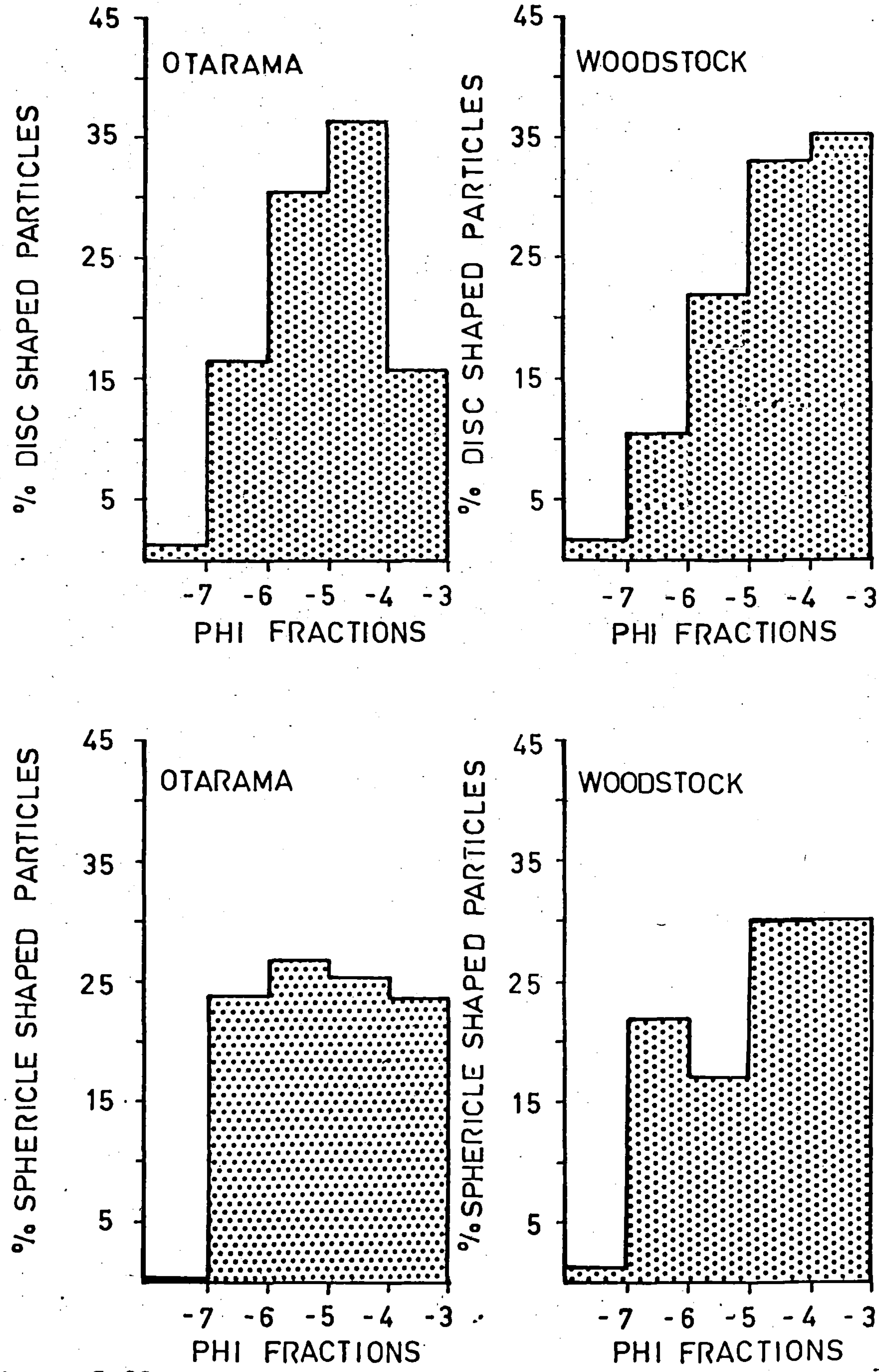


Figure 5.28 Grain size distribution of disc shaped particles (A), and spherical-shaped particles (B).

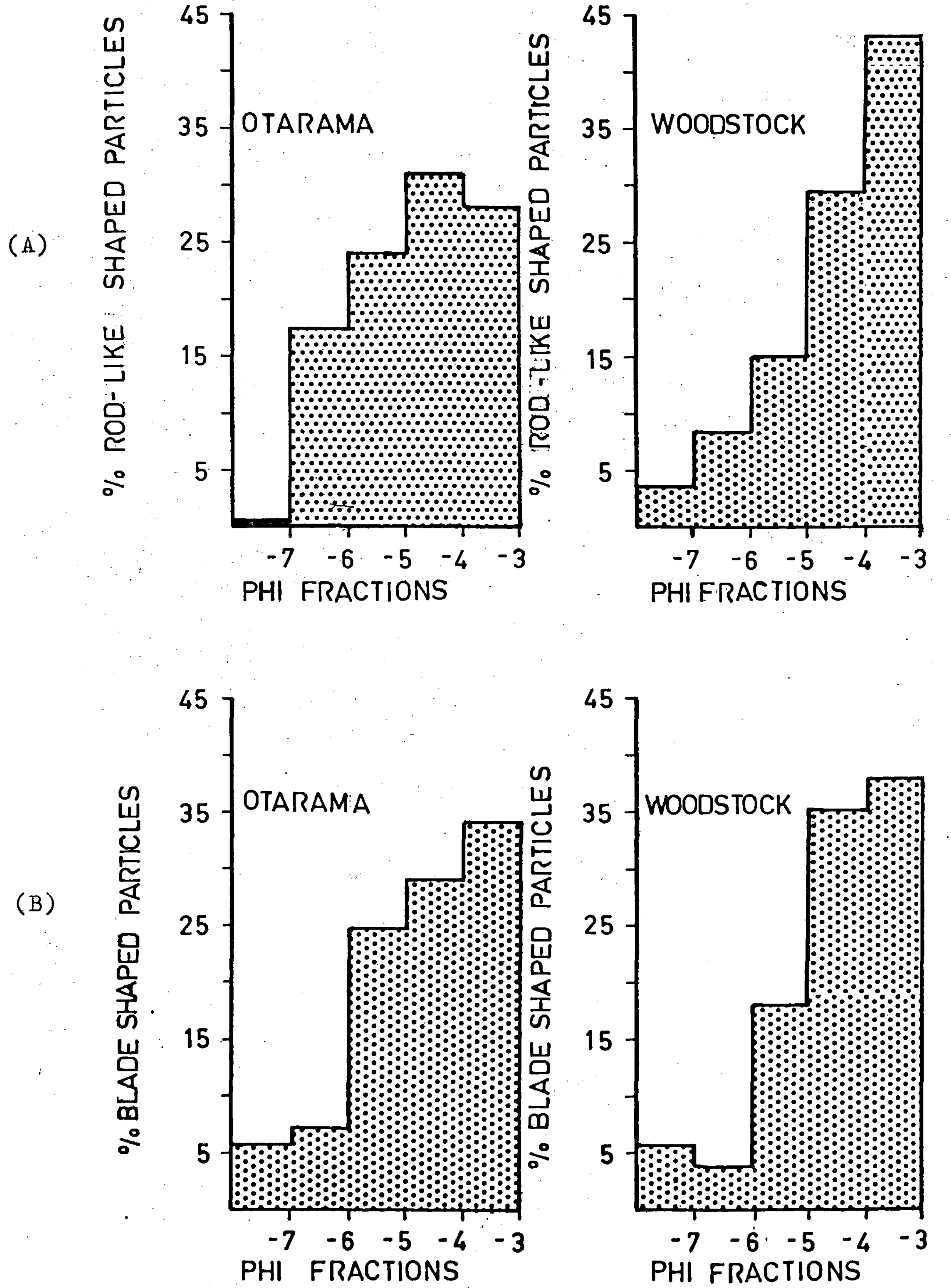


Figure 5.29 Grain size distribution of rod-like shaped (A) and blade-shaped particles (B).

the finer fractions is a reflection of the number of particles measured. (Table 17; Figures 5.28 and 5.29.)

(4) Conclusions

Disc shaped particles dominate both the Woodstock and Otarama outwash gravel deposits, as they are slightly favoured by combined crushing and abrasion processes, and hence increase the relative proportion of discs. Overall, the order of dominance of particle shapes is: disc, spherical, rod and blade.

No apparent relationship could be determined between particle shape and composition or between particle shape and grain size, however Pollack (1961) reports that "when changes in the proportions of particles do take place they are dependent on the particular mineral involved and for a given mineral, on the size of the particle."

X CONCLUSIONS

The differences in the relative abundances of the various grain size fractions between the Woodstock and Otarama outwash gravel samples, and within each sample, can be explained in terms of one or more of the following variables. These are listed in what is considered to be a decreasing order of importance.

(1) Variations in the local hydraulic conditions during deposition, this being a function of the intensity and duration of the glacial period.

(2) Selective sorting and abrasion during transportation firstly by glacial ice and secondly by stream processes,

and (3) Deficiencies of particular grain sizes within the source area.

A summary of the size distribution parameters indicated that for both samples the distribution is essentially normal, the results being very similar to those found by other authors for materials within a like environment. Small variations were found on comparing the Woodstock and Otarama samples. These apparent differences were once more explained in terms of the three previously listed variables.

The compositional count revealed the following:

(1) The apparent irregularities in the distribution of any one compositional type was partly due to the effects of an increase or decrease of other rock

types and/or their relative abundance and availability in the source area. Other factors include influx of new material and/or local sample variation.

(2) There is no evidence of rock particles of compositions 'foreign' to the Kowai or tributary catchments.

(3) Differences in the abundance, grain size distribution and grain surface characteristics of the volcanic fraction were noted to exist between the Woodstock and Otarama samples and also within each sample. Together with the bimodal distribution of the volcanic fraction within the Woodstock sample these features were able to be explained in terms of the abundance and availability of a coarse grained dolerite originating from within the Kowai Catchment and a fine grained basalt from the West Branch Kowai Catchment. The abundance and availability of each was dependent upon whether glacier ice occupied the source area to erode into the volcanics. Transportation of this material was accomplished in part by glacier ice and in part by fluvial processes.

Variations in the percentages of rock constituents are not sufficient to explain the colour variation that exists between the Woodstock and Otarama deposits at the type section. It is therefore concluded that this colour difference is in part due to (1) differing intensities of weathering processes during their respective glacial and interglacial periods, which in turn is dependent upon the time interval involved. For the Woodstock-Otarama interglacial . . .

> "The length of time is thought to have been at least some tens of thousands of years, because visual comparison of the amount of weathering compared with that shown by later deposits suggests a time span much greater than between any two subsequent glacial advances, or between the Otarama advance and the present day."
>
> (Gage, 1958.)

and (2) the intensity of, or the degree of weathering is in proportion to the age of the deposit.

The similarity in the degree of sphericity attained and the dominance of disc-shaped particles within each sample is thought to be a reflection of the importance of the mechanisms and processes operating during transportation rather than a function of the distance of transportation. This seems all the more apparent on comparing the Kowai with the non-glaciated Rubicon Catchment.

The lithology, degree of fault crushing and folding are essentially the same, but the processes of erosion and transportation differ from those that operated in the Kowai Valley.

Here, frost action and stream erosion, the dominant influences, have produced a bedload of very uniform grade, of a smaller size and range, and with greater angularity than that found in the Kowai Catchment. Because of the absence of the larger sized material in the Rubicon Valley, no amount of transportation by fluvial processes alone could produce the characteristic features attained by the outwash gravels of the Kowai Valley. Therefore, the effect of glaciation upon a valley is the production of large volumes of material of a size range capable of withstanding the processes of abrasion, crushing and breakage during transportation by glacier ice and stream processes, the end product of which approximates in range and size of the material found in the mid reaches of the Kowai Valley.

The distance between the Otarama terminal moraine and the Woodstock recessional moraine, a mere four kilometres, is considered to be insufficient for the development of significant particle parameter differences in one deposit and not the other. The constancy of the various parameters analysed between the Woodstock and Otarama outwash gravel samples, overall, is a function of source area lithology and the mechanisms of transportation rather than distance.

SECTION TWO

PART TWO

CHAPTER SIX

DIFFERENTIATION OF LATE PLEISTOCENE OUTWASH DEPOSITS BY CLAY MINERAL CONTENT

I INTRODUCTION

The identification of clay minerals either in pure form or admixture with other minerals is not always easy. In a few instances it is sufficient to use only one of the many methods now available. Usually, however, the composition of the mineral sample is complex and requires the use of two or more supplementary analytical techniques for establishing the nature of the minerals and their relative amounts. X-ray diffraction and infra-red spectroscopy have proven adequate for the identification of clay minerals in this study.

II AIM

Major criteria used to differentiate stratigraphic units of Pleistocene outwash gravel in the past have been:

(i) lithologic characters observable in the field, and

(ii) regional relationships, based on recognisable interglacial soils and major unconformities.

This investigation was designed to:-

(i) determine the clay mineralogy of the glaciofluvial deposits, and

(ii) test limitations of clay mineralogy for correlation purposes.

III LATE PLEISTOCENE STRATIGRAPHY

Good exposures of river terrace deposits are to be found along the banks of the Kowai River. The sections chosen for sampling lie within the middle reaches of the Valley, where a complex pattern of aggradational terrace deposits of Late Pleistocene age are to be found. Two of the stratigraphic sections contain outwash gravel deposits of known relative age, the physical characteristics and stratigraphic position of which were used in conjunction with the information gained from the clay mineral assemblage analysis, to determine the stratigraphic position, and hence age, of the other deposits of unknown age.

IV COLLECTION SITES

Samples of the clay fraction from nine outwash gravel units at five stratigraphic section localities were collected for analysis. Figure 6.1 shows the locality of these five stratigraphic sections.

(1) Section 1

Detailed geographic location and lithologic characteristics of this section can be found in Chapter Five. The textural analysis of the outwash gravel units, dealt with in Chapter Five, are from this stratigraphic section.

Clay sample number one was collected from the uppermost unit of gravel at this locality. It is considered to be of post glacial age. Sample number two from the middle unit was deposited during the Otarama glacial advance. Sample number three, from the lower unit, was deposited during the Woodstock glacial advance.

(2) Section II

This stratigraphic section is a river cutting situated along the left bank of the Kowai River, 100 metres upstream from the junction of the Brooksdale and Kowai Rivers. This section consists of two distinct outwash gravel units. Although both units consist of relatively unweathered greywacke boulders and are of a very similar texture and degree of compaction, they differ in that the colour of the clay content is distinct for each unit. The lower unit has a distinct yellow coloured clay while the clay fraction of the upper unit is pinkish-brown. Clay sample number 12 was collected from the lower unit

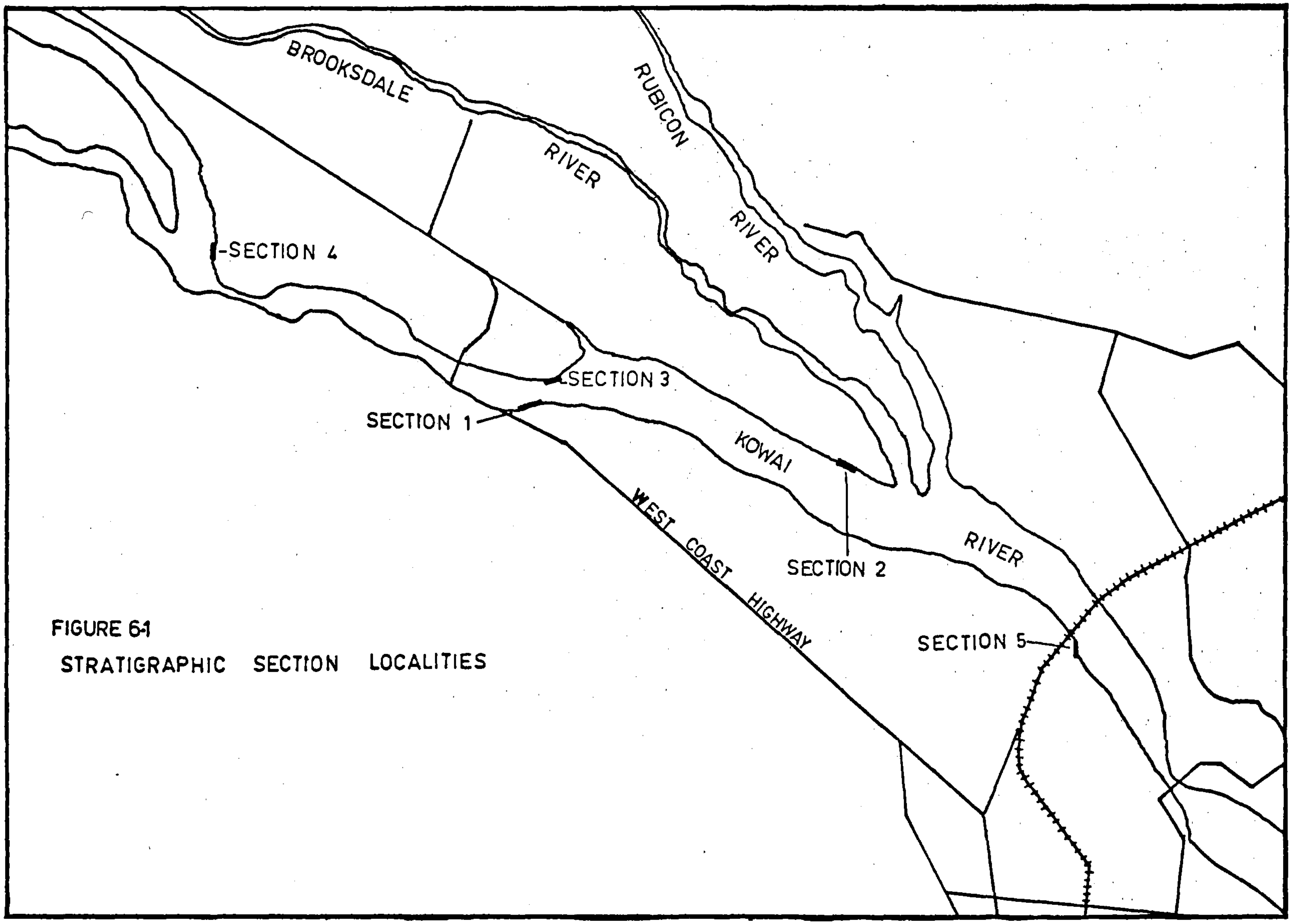


FIGURE 6-1
STRATIGRAPHIC SECTION LOCALITIES

and sample number 13 of the upper unit.

(3) Section III

Section III is a river cutting situated along the left bank of the Kowai River directly opposite section I. Sample number 19 was collected from the lower of two units found here. The upper unit is almost devoid of clay sized material. It is considered to be of an equivalent age to the uppermost unit of Section I.

(4) Section IV

Section IV is a river cutting along the left bank of the Kowai River, 0.5 kilometres upstream from the Lime Works bridge. Clay sample number 21 was collected from the lower of two units; the upper unit is of post glacial age.

(5) Section V

Section V is an exposed terrace cutting, thirty metres downstream from the West Coast Rail Bridge where it crosses the Kowai River. This section is along the right bank. Sample number five was collected from the lowermost unit. This unit was deposited during the Woodstock glacial advance. Sample number four was collected from the upper unit of this section.

V METHOD OF STUDY

The clay fraction less than 2μ in size was used in this study. Glass cylinders containing 1000 mls of water with two to three drops of calgon were left to stand for sixteen hours prior to sampling. The desirable clay-sized fraction was then pipetted from the top ten centimetres of each cylinder.

(1) Preparation of Oriented Slides

Parallel orientation specimens were made by pipetting four mls of clay-water suspension on to a flat surface, such as a glass slide or cover slip, and allowing the sample to settle out and dry slowly at room temperature.

An X-ray diffractogram of an untreated slide from 3° to 53° 2ϕ was run to determine the overall mineralogical content of the clay fraction. The principal d spacings used for identification can be found in Table 18.

One slide was treated with a 1:2 glycerine-water mixture; a second was treated with warm dilute hydrochloric acid; a third was magnesium saturated; and a fourth was heated in stages to temperatures of 110°C, 300°C, 550°C and 600°C for two hours, then allowed to cool in a dessicator before being X-rayed.

MINERAL	hkl	Principal d spacing used for identification	2ø (approx)
Kaolinite	001	7.13 - 7.16	12.36 - 12.4
Kaolinite (disordered)	001	7.15	12.38
Halloysite $4H_2O$	001	10.1	8.75
Halloysite $2H_2O$	001	7.21	12.26
Mica, 2M	002	9.99 - 10.4	8.85 - 8.80
Illite	001	10.16	8.70
Vermiculite	001	14.2	6.22
Chlorite Mg	001	14.1 - 14.2	6.27 - 6.22
Chlorite Fe	001	14.1 - 14.2	6.27 - 6.22
Quartz	001	3.34	26.66
Quartz	001	4.26	20.85
Feldspar-Orthoclase	040,202	3.25 - 3.28	27.4 - 27.16
Feldspar-Plagioclase	002,040	3.17 - 3.18	28.14 - 28.0
Biotite	002	10.1	8.77
Montmorillonite Group	001	15.4 (Variable)	5.7

Table 18 Identification by X-ray Diffraction of Clays and Associated Minerals. (Carrol, 1970.)

An X-ray diffractogram was run after each heating stage. Diffractograms of all treated slides were run from 3^o to 15^o 2ø.

A Philips Universal Diffractometer with Cuk radiation and Nickel filter was operated at 40 Kv and 20 MA, at a speed of one degree per minute and was used in conjunction with a Krypton proportional counter with a 1 degree divergence slit, a 0.2^o receiving slip and a 1 degree scatter slit. The relative humidity in the laboratory ranged between 50% and 60%.

(2) Preparation of Infra-red Spectroscopy Discs

The dried clay fraction was mixed with KBr powder and placed in a vibromil for several minutes to ensure thorough mixing. Usually 1 mg of clay specimen was mixed with 300 mgs KBr and pressed in a metal die under a pressure of 10 tonnes for approximately ten minutes. The discs were then stored in a dessicator for twenty four hours prior to their use.

Spectrographs were run on a Perkin-Elmar model 221, double-beam, infra-red spectrophotometer, over a spectral range of between 650 cm^{-1} using NaCl prisms. Spectra were obtained with scanning speed 8, nil suppression and 1x expansion.

(3) Quantitative Estimates

Measurements of the areas of the principal (001) basal spacings on X-ray diffractograms of clay minerals with a planimeter affords a useful method of comparing quantities of a mineral in a mixture (Carroll, 1970). The principal (001) spacings utilized in this study occur at approximately 6.3° 2θ (d = $14.02A^{\circ}$), 8.84° 2θ (d = $10.04A^{\circ}$) and 12.5° 2θ (d = $7.08A^{\circ}$). Peak areas are assumed to be related to percentages of the phases present (Ehlmann, 1968). The area of each principal basal spacing is presented as a percentage of the sum total of the areas beneath the three principal peaks.

Further comparisons can be made by utilizing the relative peak intensities of the principal (001) spacings. The background must be determined and subtracted from the peak intensities before any quantitative estimates can be made.

The $7A^{\circ}:14A^{\circ}$ intensity ratio affords information on the variety of chlorite present.

> "The $7A^{\circ}:14A^{\circ}$ intensity ratio for chlorite is about 1:1 for the magnesium rich varieties and about 3:1 for the iron rich varieties (Brindley, 1951 Table 14)."
> (Droste, 1956)

More specifically this ratio was determined in order to establish whether or not it could be used as an indicator of the degree of weathering, as it has been reported in the literature that ". . . the ratio decreases in more weathered material". (Droste, 1956.)

These measurements are not intended to be an absolute assessment of quantitative mineral composition, but serve only as a means of comparison among samples.

VI CLAY MINERALOGY OF THE GLACIOFLUVIAL DEPOSITS

(1) General

(a) X-Ray Diffraction Results. The non-clay mineral components include quartz, feldspar and amphiboles. No quantitative estimates of these components was attempted.

The clay mineral assemblage consists of illite, kaolinite and a "mixed-layer mineral", "Mixed-layer mineral" includes all clay materials with a basal reflection occurring at approximately 6.25° 2ϕ to 6.3° 2ϕ (d = $14.2A^{\circ}$ to $14.02A^{\circ}$). Their basal spacing expands and the reflection shifts to between 6.1° 2ϕ (d = $14.48A^{\circ}$ and $14.97A^{\circ}$), after glycerine treatment. Higher order basal reflections of this mineral are usually too weak to be recognised on the diffraction patterns from air dried samples. Some high order basal reflections can be detected from glycerine-treated samples, but they are not in rational series. Treatment with warm dilute hydrochloric acid affected the $14A^{\circ}$ peak to varying degrees in each sample, as the content and state of crystallinity of the 'mixed layer mineral', differed considerably from sample to sample.

Heating to low temperatures generally effected a collapse or partial collapse of the clay mineral structure while temperatures of 300°C resulted in a shift of the 14A° basal spacing. Heating to 550°C caused the first order basal reflection to further collapse and shift to anywhere between 7.25° 2ϕ (d = 12.2A°) and 7.75° 2ϕ (d = 11.48A°). Higher order basal reflections shift correspondingly. The first order basal reflection is intensified by heating to 600°C for two hours.

These characteristics suggest that the 'mixed-layer mineral' is composed of randomly interstratified layers of vermiculite-mortmorillonite-chlorite. The proportions of each constituent vary from sample to sample and explain the variety of behavioural characteristics in response to the various treatments. Figures 6.3, 6.4 and 6.5 show diffractograms depicting the responses of the clay minerals to the treatments undertaken in this study.

Illite was indentified by a series of basal reflections that occur at 8.84°, 19.63° and 26.7° 2ϕ, corresponding to d values of 10.04A°, 4.4A° and 3.33A° respectively. The abundance of illite is a reflection of source material. It appears that most of the illite was derived from muscovite and is therefore detrital in origin. Illite was not affected by any of the treatments.

The Kaolin Group clay mineral was identified by two basal reflections that occur at 12.5^{o} and 24.9^{o} 2θ, corresponding to <u>d</u> values of $7.08A^{o}$ and $3.6A^{o}$. These basal spacings do not change upon glyceration or heat treatments but are reduced in intensity by hydrochloric acid treatment due to the presence of chlorite which also has a basal reflection at 12.5^{o} 2θ (d = 7.08A).

Heating to low temperatures affects the intensity of this peak, the degree of which depends on the crystallinity of the clay mineral. The Kaolin Group clay is completely destroyed upon heating to $550^{o}C$ for two hours. It was not a major constituent in any of the samples analysed.

Selected examples of diffractometer traces of oriented, treated samples are given in figures 6.3, 6.4 and 6.5.

(b) <u>Infra-red Spectroscopy Results</u>. The infra-red absorption patterns for all the samples analysed are characterised by "free" hydroxyl (O-H) absorption at 2.7 microns and 2.85 microns, and a comparatively lesser amount of hydrogen bonded hydroxyl up to 3.5 microns. (Figure 6.2.)

The band between 3.5 microns and 6.5 microns is relatively featureless, except that free water, (H-O-H), absorption occurs at 6.05 microns.

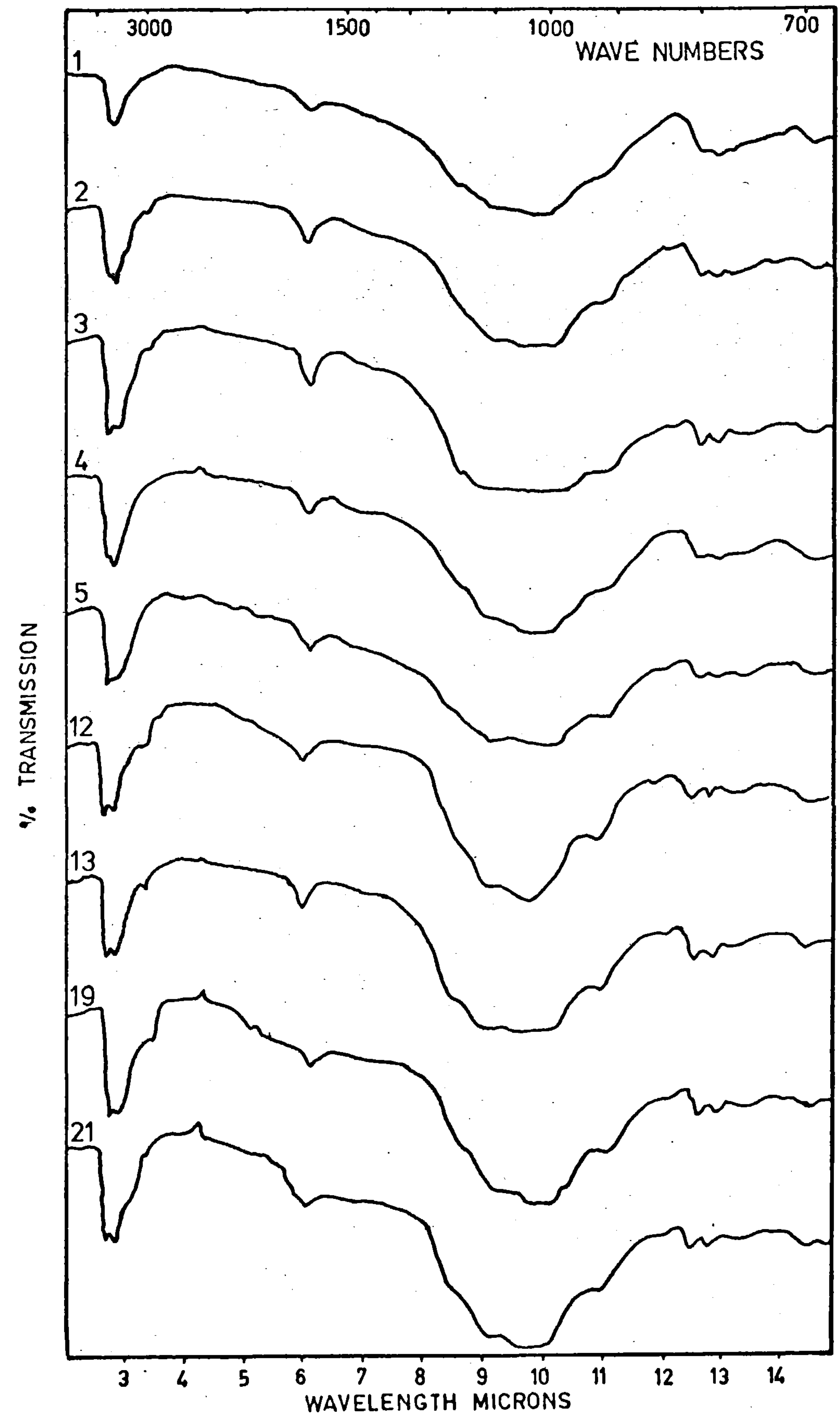


Figure 6.2 Infra-red Spectra of the Clay Mineral Assemblage.

Absorption begins at about 6.5 microns and increases regularly in intensity to approximately 8.6 microns where a change in slope of the absorption curve indicates increased absorption of α quartz (Nanin, 1955, Table 1). Another peak of slightly greater absorption occurs at about 8.95 microns to 9.05 microns. A small absorption peak at 9.15 microns has been identified as belonging to the Kaolin Group by Keller and Pickett (1950).

Work by Keller, Spotts and Biggs (1952) indicates that the phyllosilicates or sheet silicates, of which the clays are representatives, are characterised by one main absorption band centered between 9.0 microns and 10.0 microns. This position is assigned to the S_1O_4 group. Unfortunately qualitative analysis from infra-red spectra of a clay mineral assemblage was difficult, as the major diagnostic peak positions of each constituent were found to be insufficiently resolved, because of interference of absorption spectra within this broad band. Usually spectra of montmorillonite, illite and muscovite are very similar, except that muscovite has a pronounced absorption of 9.35 microns. Montmorillonite and illite are difficult to distinguish, although it has been stated (Hunt <u>et.al</u>., 1950) that this may be done on the basis of the peak position of the strongest band, 9.6 microns in montmorillonite and 9.7 microns in illite.

A distinct absorption peak occurs at 10.95 microns. This is common to kaolin, halloysite, illite and montmorillonite, however Nanin, 1955, suggests that kaolin can be distinguished from halloysite on the basis of different spectra. Kaolin has a doublet at 10.68 microns and 10.95 microns, whereas halloysite has a singlet at 10.95 microns. The infra-red absorption peaks of clay samples from Late Pleistocene outwash deposits show only a single absorption peak at 10.95 microns. It is therefore suggested that the member of the Kaolin Group present in these samples is halloysite and not kaolin as was previously determined from X-ray diffraction results. A small absorption peak at 12.05 indicates the presence of illite (Nahin, 1955).

Quartz has a well defined spectrum with major absorptions at 8.6 and 9.2 microns and a diagnostically useful doublet at 12.5 and 12.8 microns. A smaller less significant quartz absorption peak occurs at 14.4 microns (Figure 6.2).

(2) <u>Classification of Samples</u>

On the basis of the results obtained, a classification based upon:-

1. The order of relative peak intensities of the three principal basal spacings,

2. the peak area of the three principal basal spacings, and

3. The $7A^o:14A^o$ intensity ratio, has been proposed.

The groups and their distinguishing characteristics are briefly stated below.

(a) Group A. This group is characterised by a very high relative peak intensity at 12.5^o 2ϕ ($d = 7.08A^o$), a moderate relative peak intensity at 8.8^o 2ϕ ($d = 10.04A^o$) and a low relative peak intensity at 6.3^o 2ϕ ($d = 14.02A^o$) (Figure 6.3). The peak area percentages for the $7.08A^o$, $10.04A^o$ and $14.02A^o$ basal spacings are approximately 40%, 36% and 24% respectively. The $7A^o:14A^o$ peak intensity ratio is 2:1, thereby indicating a mixed Fe-Mg Chlorite that has undergone little to no weathering. The sharpness of the X-ray diffractogram peaks indicate that the chlorite, halloysite and illite clay minerals are relatively well crystallized.

Treatment with warm dilute hydrochloric acid reduced the peak intensities but the relative peak order remained constant.

Heating to low temperatures further reduced the peak intensities but again the relative peak order remained unaffected. However, heating to 300^oC did alter the relative peak order while heating to 550^oC almost completely destroyed the $7A^o$ peak. At 600^oC the $7A^o$ peak was completely destroyed while the $14A^o$ peak at 6.3^o 2ϕ intensified markedly. The basal positions of the three principal peaks remained

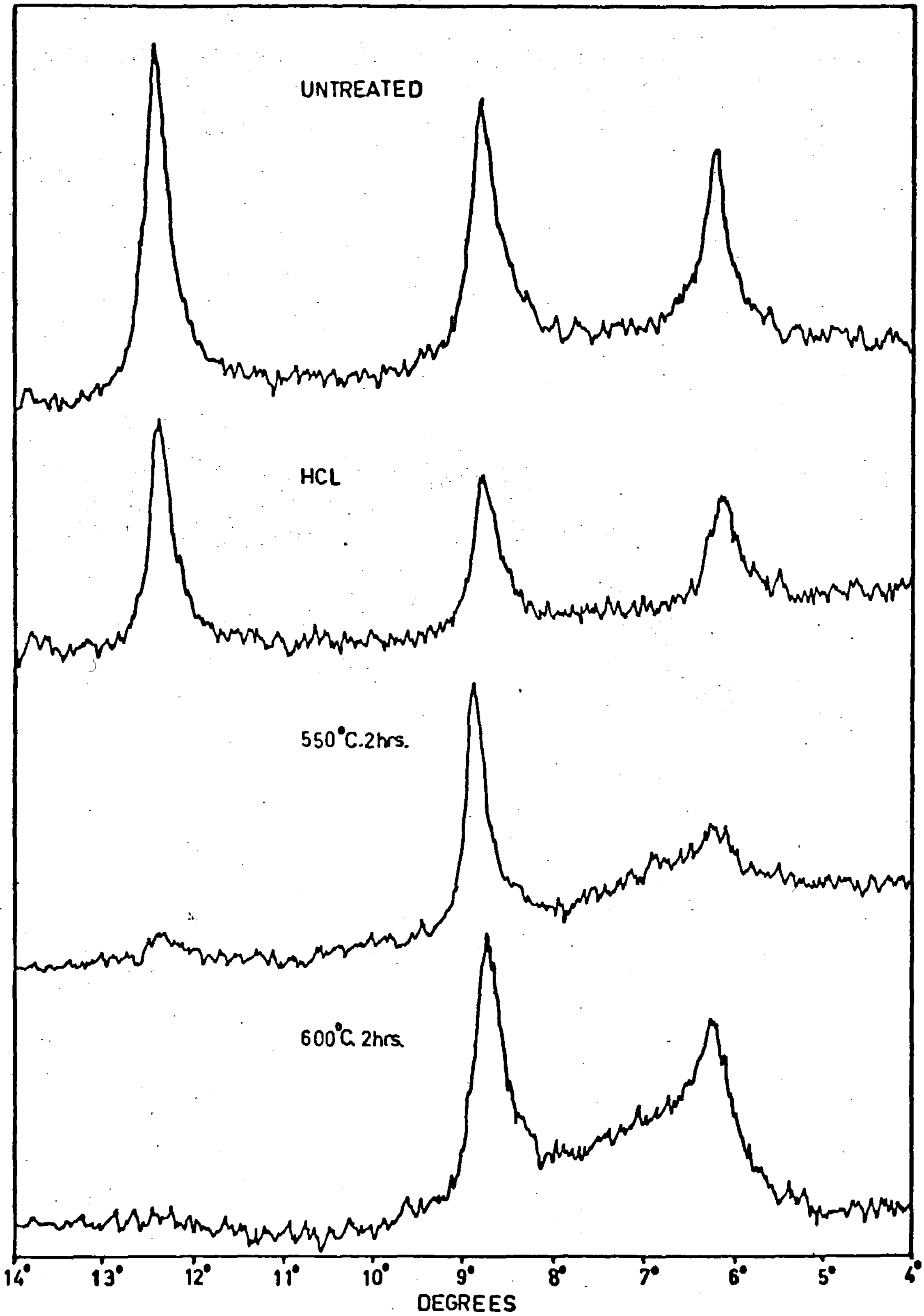


Figure 6.3 X-Ray Diffractograms showing behaviour characteristics of the clay mineral assemblage typical of samples in Group A.

fixed throughout the various treatments.

The gain in intensity and the position of the basal spacing of the 14A^o peak on heating to high temperatures confirms the presence of chlorite and the absence of any expandable clay minerals.

The behaviour of the 7A^o peak (12.5 2ϕ) suggests the presence of a small amount of a Kaolin Group mineral, probably halloysite, together with a substantial amount of well crystallized chlorite.

No change in response of the 10A^o peak (8.8^o 2ϕ) towards the various treatments together with the relative intensity of this peak, confirms the presence of a considerable amount of illite.

(b) Group B. In general, this group is characterised by a high relative peak intensity of 8.8^o 2ϕ (d = 10.04A^o), a moderate relative peak intensity at 6.3^o 2ϕ (d = 14.2A^o) and a low relative peak intensity at 12.5^o 2ϕ (d = 7.08A^o) (Figure 6.4). However, variations in the relative peak intensities do occur within this group but are not of sufficient magnitude to be considered significant, as they remain distinct from either Group A, or Group C. One such variation occurs where X-ray diffractograms of several clay samples show the 14A^o and 10A^o peaks to be of the same relative intensity. This is borne out by the fact that peak area percentages for these same samples are of the same order of magnitude as their relative peak intensities. Samples 12 and 19 show such a variation. (Table 19).

Sample Number	Peak area % for the Principal Basal Spacings		
	10A°	14A°	7A°
19	40.0%	40.0%	20.0%
12	38.7%	38.7%	22.6%
13	41.65%	41.65%	16.7%
2	49.0%	28.0%	23.0%

Table 19 Peak area percentages for the principal basal spacings of samples in Group B.

A second variation occurs where the X-ray diffractograms exhibit the characteristic relative peak intensity order for this Group but the peak area percentages of the 10A° and 14A° peaks are identical. This variation is shown by sample 13 (Table 19).

X-ray diffractograms for sample 21 reveal yet a third variation within this group, in that the relative peak intensity order is characteristic of those samples within Group C (Table 20). However, the difference in intensity between the 14A° and 10A° peaks is so small as to be considered insignificant. This is substantiated, in part, on comparing the peak area

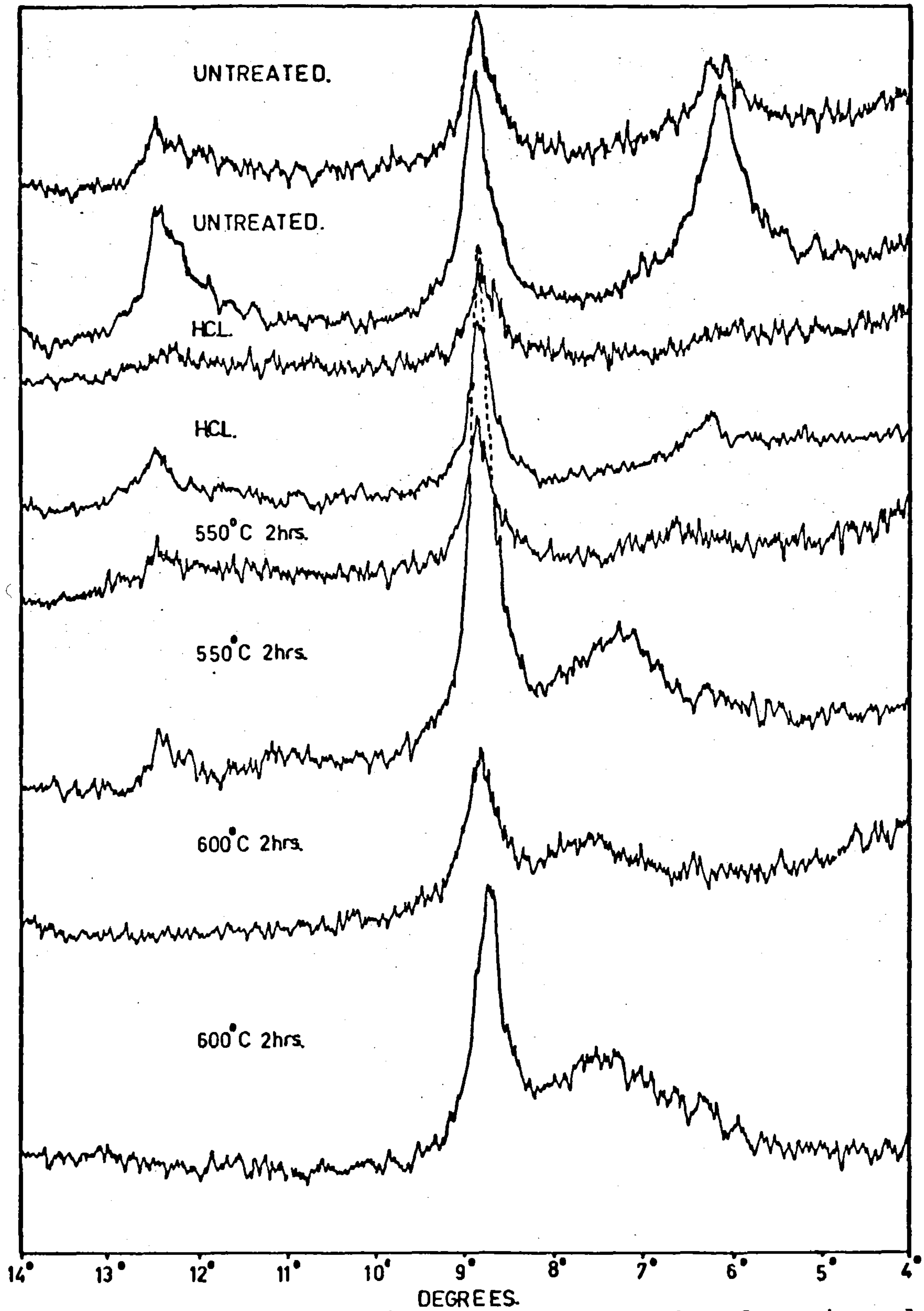


Figure 6.4 X-Ray diffractograms of the clay mineral assemblage typical of samples in Group B. Sample 2 is appreciably more weathered than sample 12.

percentages of these two basal spacings for sample 21 with other samples within this group. It is evident that the peak area percentages are of the order of magnitude characteristic of Group B and not Group C.

Sample Number	Peak area % for the Principal Basal Spacings		
	$14A^o$	$10A^o$	$7A^o$
21	41.9%	37.2%	20.9%

Table 20 Peak area percentage for the principal basal spacings of sample 21.

The 7A:14A intensity ratio for samples 2 and 19 are identical, being 1:1.5. For sample 13 the ratio is 1:1.1, for sample 12 it is 1:1.3 and for sample 21 the ratio is 1:1.4. These ratios are distinct from those determined for clay mineral samples from groups A and C.

Treatment with warm dilute hydrochloric acid reduced the $14A^o$ and $7A^o$ peaks to residual mounds, on the X-ray diffractograms, thereby indicating the presence of chlorite.

Glycerine and water caused expansion of the d spacings of the 14A peak from 6.3^o 2ϕ (d = $14.2A^o$)

to 5.9^{o} 2ϕ (d = $15.0A^{o}$) suggesting the presence of a smectite, possibly montmorillonite.

Heating to $100^{o}C$ effected a reduction of the $7A^{o}$ and $14A^{o}$ peaks, more so the $14A^{o}$ peak. The $7A^{o}$ peak was completely destroyed on heating to $550^{o}C$ indicating the destruction of the halloysite structure. At $550^{o}C$ a basal spacing change occurs from 6.3^{o} 2ϕ (d = $14.2A^{o}$) to between 7.5^{o} 2ϕ (d = $11.78A^{o}$) and 7.75^{o} 2ϕ (d = $11.48A^{o}$). This basal spacing change varies from sample to sample. The shift indicates the presence of a mixed-layered clay showing characteristics of montmorillonite and vermiculite, interlayered with chlorite. This basal spacing change on heating distinguishes samples within Group A from those in Group B and is evidence for the first signs of the alteration of an essentially chloritic clay to a chlorite-montmorillonite-vermiculite mixed-layer mineral.

Heating to $550^{o}C$ and above produces a shoulder peak on the X-ray diffractograms, resulting from the collapse of the $14A^{o}$ clay mixture. (Figure 6.4.) This indicates reinforcement of the $14A^{o}$ diffraction peak and collapse of some $14A^{o}$ _d_ spaces to $10A^{o}$. This shoulder, at approximately $12.6A^{o}$ was produced by interstratified material, in which some layers collapsed at the temperatures at which chlorite layers reinforce the $14A^{o}$ peak.

(c) <u>Group C</u>. This group is characterised by a very high relative peak intensity at 6.3^o 2ϕ ($d = 14.2A^o$), a moderate relative peak intensity at 8.8^o 2ϕ ($d = 10.04A^o$) and a low relative peak intensity at 12.5^o 2ϕ ($d = 7.08A^o$) (Figure 6.5). For all samples within this group the order of the relative peak area percentages for the principal basal spacings, corresponds to the order of the relative peak intensities. The relative peak area percentages for the principal basal spacings are given in Table 21.

Sample Number	Peak area % for the Principal Basal Spacings		
	$14A^o$	$10A^o$	$7A^o$
3	52.2%	30.4%	17.4%
5	46.2%	34.6%	19.2%
4	48.3%	34.5%	17.2%

Table 21 Peak area percentage for the principal basal spacings of samples in Group C.

The X-ray diffractograms of untreated slides show the $7A^o$ peak to be broad and of low intensity. This decreased peakedness, particularly for samples within groups B and C is thought to indicate poor crystallinity of the clay minerals and high amorphous content.

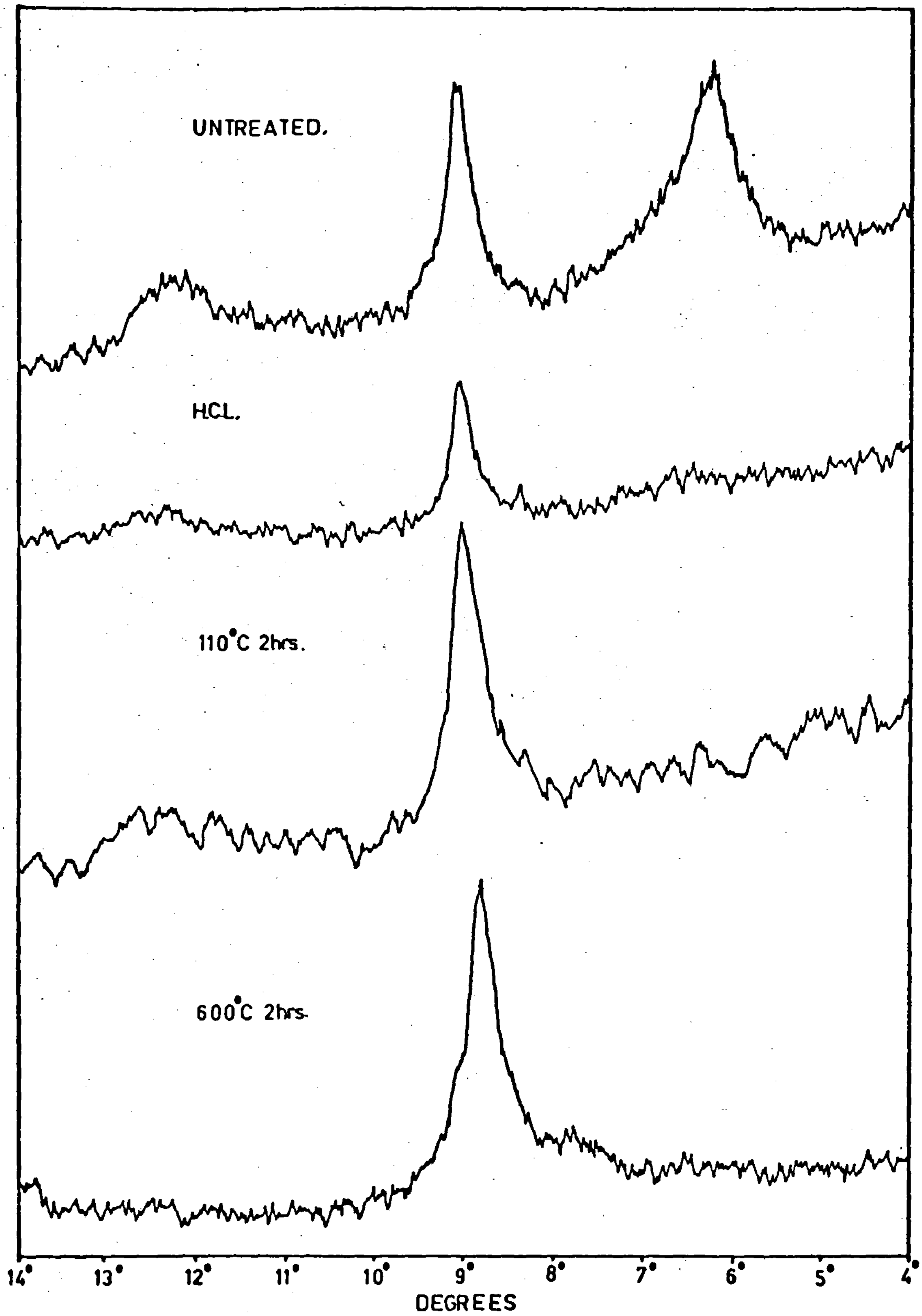


Figure 6.5 X-ray diffractograms showing behaviour characteristics of the clay mineral assemblage typical of samples in Group C.

Treatment with warm dilute hydrochloric acid almost completely destroyed the 7A^{o} and 14A^{o} peaks, indicating substantial chlorite content. Glycerol and water treatment expanded the basal spacing of the 14A^{o} peak from 6.3^{o} 2ϕ (d = 14.2A^{o}) to 6.1^{0} 2ϕ (d = 14.48A^{o}).

Heating to 110^{o}C reduced the 7A^{o} and 14A^{o} peaks to residual mounds on the X-ray diffractograms for samples 4 and 5 and completely destroyed both peaks in sample 3.

At 550^{o}C a high shoulder peak develops on the side of the 10A^{o} peak indicating a basal spacing shift at the 14A^{o} peak towards the 10A^{o} peak. The basal spacing change effected is from approximately 6.3^{o} 2ϕ (d = 14.0A^{o}) to 7.75^{o} 2ϕ (d = 11.47A^{o}) where the peak remains, distinct from the 10 A^{o} peak. The explanation for this basal spacing shift is identical to that given in the last paragraph under Group B.

The 7A: 14A relative peak intensity ratio for the samples in Group C are distinct from those of the previous two groups. For sample 3, the ratio is 1:3 and for sample 5 the ratio is 1:2.8. Both samples are from deposits of Woodstock age. Sample 4 has a 7A:14A ratio of 1:2.4. While this sample has the characteristic relative peak intensity order (Table 21) and 7A^{o}:14A^{o} peak intensity ratio to be classified under Group C, the sample was in fact collected from a deposit of somewhat younger age and hence should be classified under Group B.

Objective measures of the groupings have not been statistically analysed to test their validity, however, the clay mineral assemblages are still considered to be diagnostic features of these fluviatile deposits.

(3) The Chloritic Clay Mineral and Its Alteration Product

The chlorite component within the clay mineral fraction of samples collected from various outwash gravel horizons is detrital in origin. Chlorite is one of the principal clastic grains within sandstones and argillites belonging to the 'Torlesse Facies'. The clayey matrix of argillites consists of a sericite and a slightly recrystallized chlorite.

A second source of chlorite results from the reworking of Tertiary marine sediments. These were at one time more widely distributed within the Kowai Catchment, but have since been reduced to a small infaulted outlier to be found in the West Branch Kowai Catchment.

The chloritic content of the samples classified in Group A appears to be well crystallized. The deposits from which these samples were collected are of post glacial age and are not appreciably weathered.

The chloritic content of samples from older weathered outwash gravel deposits (Groups B and C), has undergone progressive alteration under the influence of weathering by the formation of expandable layers, resulting in a mixed-layer structure. The mechanism is oxidation of iron in the octahedral layers or the replacement of potassium in illite by the hydronium ion (Harrison and Haydn, 1957).

Chlorite is the most unstable of the clay minerals when subjected to weathering (Droste, 1956). Weaver (1956) is also of the opinion that chlorite is very easily weathered. On this basis the weathering of chlorite to collapsible material is a possible explanation for the collapse of chlorite on heating to 550°C. This, together with the cation exchange values, indicates the presence of collapsible layers interstratified with chlorite layers.

VII THE CLAY MINERAL ASSEMBLAGE AS A MEANS OF CORRELATION

The question now arises as to whether the clay mineral assemblage within each group is sufficiently different to permit distinguishing between outwash gravel horizons of varying ages. The clay mineral assemblage of samples within groups A and C are significantly different.

Samples within group A are dominated by well crystallized chlorite together with a very small amount of a Kaolin Group clay mineral, possibly halloysite. Illite is a major constituent also.

Group C samples are dominated by a mixed-layered mineral consisting of chlorite, vermiculite and a small amount of montmorillonite. Once again illite is a major constituent within samples of this group.

Samples in Group A were collected from deposits of suspected post glacial age while those in Group C are from outwash gravel horizons deposited during the Woodstock glacial advance.

The physical characteristics of these two deposits in outcrop are such that there can be no mistaking them in the field. The most noticeable feature is the difference in the degree of oxidation, which appears to be reflected by differences in the state of weathering of the clay mineral assemblage. In the case of these two deposits the clay mineral assemblage could be used for purposes of correlation in conjunction with the more apparent and well established methods, particularly stratigraphic position and degree of weathering.

However, horizons of outwash gravel belonging to at least three glacial episodes intermediate between the youngest and oldest deposits described above, in terms of stratigraphic position and degree of weathering, all have a very similar clay mineral assemblage. This clay mineral assemblage has characteristics intermediate between the clay assemblage of Groups A and C. These samples constitute Group B. The clay mineral assemblage characteristic of Group B does vary slightly from sample to sample. However, the differences are not of a sufficient magnitude or reliability to permit distinction between horizons of outwash gravel deposited during the Otarama, Blackwater I and Blackwater II glacial advances.

The absence of a distinct clay mineral assemblage within each of these three outwash gravel horizons within Group B, is thought to be a reflection of insufficient time separating the glacial episodes to permit the establishment of a distinctive clay mineral assemblage.

VIII THE 7A°:14A° RATIO AS A MEANS OF CORRELATION

The magnitude of the 7A°:14A° ratio is distinct for each of the three groups outlined in the preceding discussion. While no faith can be placed in the absolute values attained, there does seem to be a correlation between the magnitude of the 7A°:14A° ratio and the degree of weathering of outwash gravel deposits.

Stratigraphic Section I shows three distinct aggradational units of outwash gravel exhibiting an increased degree of oxidation from top to bottom.

The 7A:14A ratio decreases accordingly from 2:1 in the upper unit, to 1:1.5 in the middle unit, to 1:3 in the lowermost unit. As the magnitude of this ratio appeared to be characteristic for each of the three deposits, the limitations of its use were tested upon deposits of uncertain stratigraphic position and age. Section II was chosen for this exercise. Here, two horizons of outwash gravel were sampled, both clay samples being categorised within Group B. The lower unit is slightly but not appreciably more weathered than the upper unit. Both these deposits are appreciably less weathered than the middle unit of Section I and more weathered than the upper unit of Section I. Therefore, the 7A:14A ratio for both the samples collected from this stratigraphic section should be of a similar magnitude to other samples within Group B and hopefully of a slightly lesser magnitude than the 7A:14A ratio for the sample taken from the middle unit of Section I.

The 7A:14A ratio determined for the sample taken from the upper unit turned out to be 1:1.1 while that for the samples collected from the lower unit was established as being 1:1.3.

As the degree of weathering is taken to be an indication of relative age, the 7A:14A ratio suggests that the deposits sampled from Stratigraphic Section II are younger than the middle horizon of Section I and older than post clacial deposits. From other lines of evidence it has been established that the deposits comprising Stratigraphic Section II were deposited during glacial advances of Blackwater I and II ages.

The 7A:14A ratio for sample 19 from Stratigraphic Section III is identical to that for the sample taken from the middle unit of Section I, that is, 1:1.5. This would indicate that both deposits are of the same age. Stratigraphic information and lithologic characteristics seem to indicate that this is so.

The 7A:14A ratio for the sample taken from the lowermost unit of Stratigraphic Section V corresponds closely to the ratio established for the lowermost unit of Section I. Both horizons were deposited during the Woodstock glacial advance. The ratio for the unit sampled at Section V was established as being 1:2.8 compared to 1:3 for the sample collected from Section I.

A sample collected from a gravel horizon deposited upon the lower unit at Section V was categorized into Group C based upon relative peak intensity and peak area percentage of the three principal basal spacings, in an earlier section. The 7A:14A ratio for this same sample is 1:2.4 which is again characteristic of samples in Group C. However, this deposit is definitely not of the same age as the unit underlying it at Section V as it lacks the obvious deep physical weathering characteristics of this lower deposit of known age.

While no limits for the magnitude of the $7A^{o}:14A^{o}$ ratio have been defined for each group, it is felt that a ratio of 1:2.4 is more closely akin to the ratio established for samples taken from horizons deposited during the Woodstock glacial advance than for samples taken from horizons deposited during the Otarama Glacial advance.

It is obvious therefore that this ratio is not infallible as a means of correlation. However, if used in conjunction with other available forms of correlation it is hoped that it will prove to be of future use.

IX CONCLUSIONS

X-ray diffraction and infra-red spectroscopy have proven adequate for the identification of clay minerals in this study. The infra-red absorption spectra of clays are at present of limited usefulness for the purposes of qualitative and quantitative analysis of complex and unknown mineral mixtures.

The classification based upon: (1) the order of the relative peak intensities of the three principal basal spacings, (2) the peak areas of the three principal basal spacings, and (3) the $7A^{o}:14A^{o}$ intensity ratio was applied with moderate success.

The clay mineral assemblage is not significantly different between outwash gravel horizons of varying ages unless the time interval between periods of successive deposition is sufficiently long to reflect the climatic imprint of the interglacial periods within a single source rock and climatic zone.

The clay mineral assemblage is essentially detrital in origin and reflects primarily the character of the source area. However, in older deposits, weathering processes have altered chlorite to produce collapsible, expandable layers of interstratified montmorillonite and vermiculite, resulting in a mixed-layer structure.

All the weathering within each of these glacial outwash deposits, is thought to have occurred during the succeeding interglacial period, prior to being buried by younger deposits. This view is held on the grounds that none of the buried deposits show signs of the development of 'zones' of weathering due to the possible downward percolation of solutions once the deposit had been buried. That is, each unit of gravel is of a uniform degree of weathering throughout, and its clay mineral assemblage is identical between its contact with the overlying younger unit and the basal unit.

It is therefore concluded that the clay mineral assemblage within each gravel unit is not a product of the total time since deposition but rather a reflection of the duration and climate of the succeeding interglacial interval prior to burial by deposits of a younger glacial episode.

For the purposes of correlation the clay mineral assemblage and the 7A:14A intensity ratio are of limited use, however, if used in conjunction with other available forms of correlation including stratigraphic position and degree of weathering it is hoped that the above analytical techniques will prove to be of future use.

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